ÖAW AUSTRIAN ACADEMY OF SCIENCES

SMI - STEFAN MEYER INSTITUTE

Studies of antiproton annihilation at rest with nuclei

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Antiproton-nucleus interactions and related phenomena

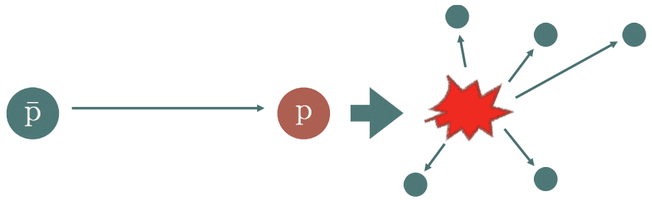
ECT* Trento, 17-21 June 2019

Outline

- **Antiproton - nucleus annihilation**
- **Motivation and goal for this study**
- **Overview of the measurement**
  - **Timepix3**
- **Data analysis and comparison with GEANT4 simulations**
- **Conclusions and further work**

Antiproton annihilation with nucleon

- **Antiproton-nucleon annihilation**



π, K (charged and neutral)

~1880 MeV energy ⇒
5 x 140 MeV/c² (rest mass)+
~230 MeV/pion (kinetic energy)

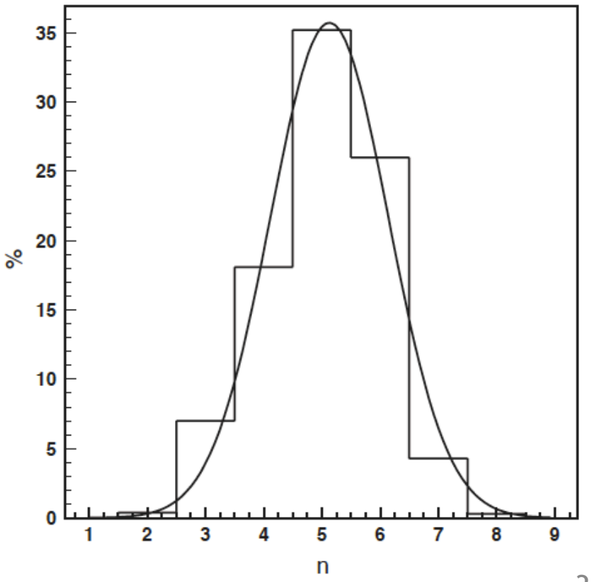
 # π/annihilation:

3.05 ± 0.04 π^+, π^-
1.93 ±0.12 π^0
4.98 ± 0.35 **total**

- **Nucleons (N) are not elementary particles ⇒annihilation takes place at the quark level.**
- $N\bar{N}$ **annihilation ⇒ all the quark-antiquark pairs do not necessarily annihilate.**
- $\bar{p}p \setminus n\bar{p}$ **annihilations still being actively studied ⇒ not even the rates of the different decay channels are completely known.**

	BNL, CERN and Crystal Barrel
2 pions	0.38 ± 0.03%
3 pions	7.4 ± 0.3%
4 pions	18.1 ± 1.8%
5 pions	35.2 ± 3.7%
6 pions	23.3 ± 2.8%
7 pions	3.3 ± 0.3%

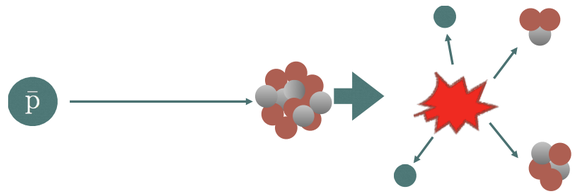
#pions per $p\bar{p}$ annihilation



Eberhard Klempt, Chris Batty, and Jean-Marc Richard. The antinucleon-nucleon interaction at low energy; annihilation dynamics. Physics Reports, 413(4–5):197–317, 2005.

Antiproton annihilation with nucleus

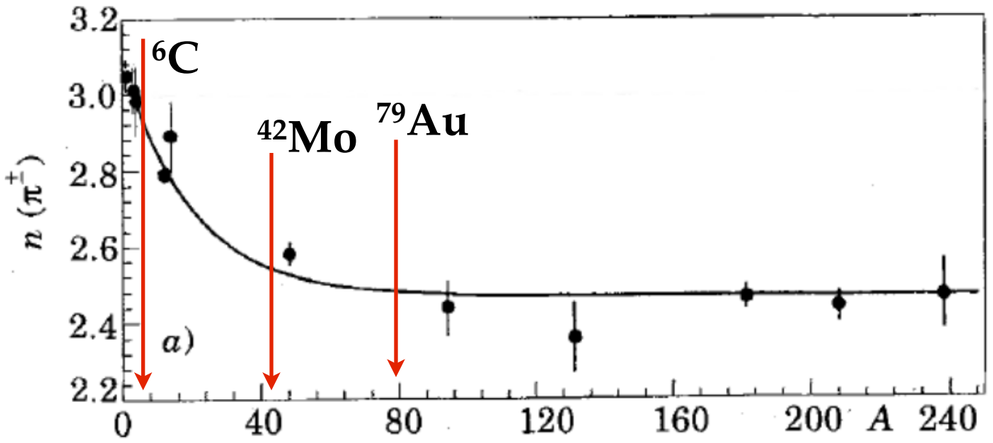
- **Antiproton-nucleus annihilation**



π and p, t, n, α, ^{3}He, ^{4}He, ^{6}He, ^{8}He, Li...

- **Capture of antiproton into bound atomic orbits with high *n*.**
- **Highly excited pbar-atom -> cascades downward (Auger electrons and X-ray emission).**
- **Annihilation at the nuclear surface, at a max depth where the density is 10% of the central nuclear density, e.g. *n* = 9 (for lead) and *n* = 4 (for oxygen).**

- **Antiproton-nucleon annihilation at rest releases an energy of 1880 MeV and produces on average five pions.**
- **Depending on the size of the nucleus -> different probabilities for the number of the primarily produced pions that will penetrate inside the nucleus.**
- **Residual nucleus ⇒ decay mechanism according to the excitation energy (Intranuclear Cascade Model, INC):**



G. Bendiscioli and D. Kharzeev. Antinucleon-nucleon and antinucleon-nucleus interaction. a review of experimental data. La Rivista Del Nuovo Cimento Series 3, 17(6):1–142, 1994

Carlo Guaraldo. Low energy antiproton-nucleus annihilation. Nuclear Physics B - Proceedings Supplements, 8(0):243 – 254, 1989

Physics motivation

- **Annihilation/fragmentation models validation:**
  - **CHIPS** (CHiral Invariant Phase Space): a quark-level, 3D event generator for the fragmentation of excited hadronic systems into individual hadrons.
  - **FTFP** (FriTjoF Precompound): relies on a string model to describe the interactions between quarks.
  - **FLUKA** (FLUktuierende KAskade): hadron-nucleon inelastic collisions are described at hadron level, in terms of resonance production and decay up to a few GeV (PEANUT model).
  - **None of the models is using annihilation data at rest on nuclei, all are theory-driven interaction models.**
- **To collect data for a systematic study of the:**
  - **Average multiplicity.**
  - **Energy distribution of the annihilation fragments.**
- **Tuning of Monte Carlo simulations (GEANT4): detector design and performance estimate relies on them.**

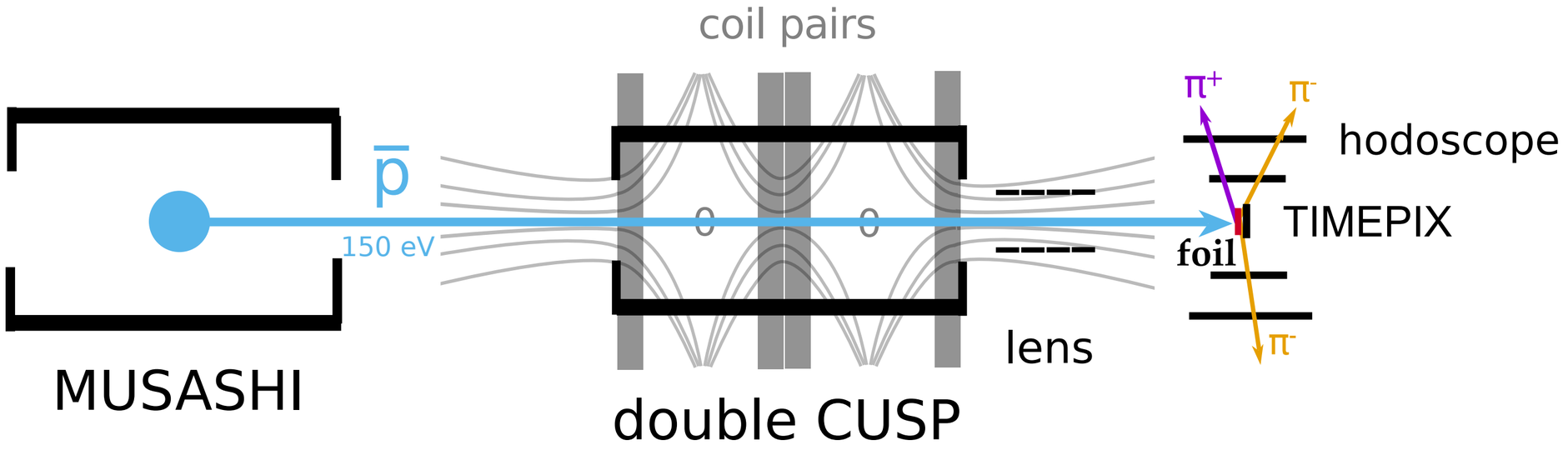
Antiproton-nuclei annihilation in GEANT4 models

- **CHIPS:**
  - **Abandoned in GEANT4 as of v.10.0**
    - **QGSP_BERT_95 with GEANT4 v.9.6 p.02**
    - **At high energies (E>20 GeV): high-energy string model (Quark-Gluon String) - QGSP.**
    - **For medium energy the intranuclear (INC) cascade model BERT (instead of the alternative BIC);**

- **FTFP:**
  - **FTFP_BERT_TRV with GEANT4 v.10.0**
  - **At high energies (E>20GeV): Fritiof-like String model (FTF)**
  - **For medium energy the intranuclear (INC) cascade model BERT**

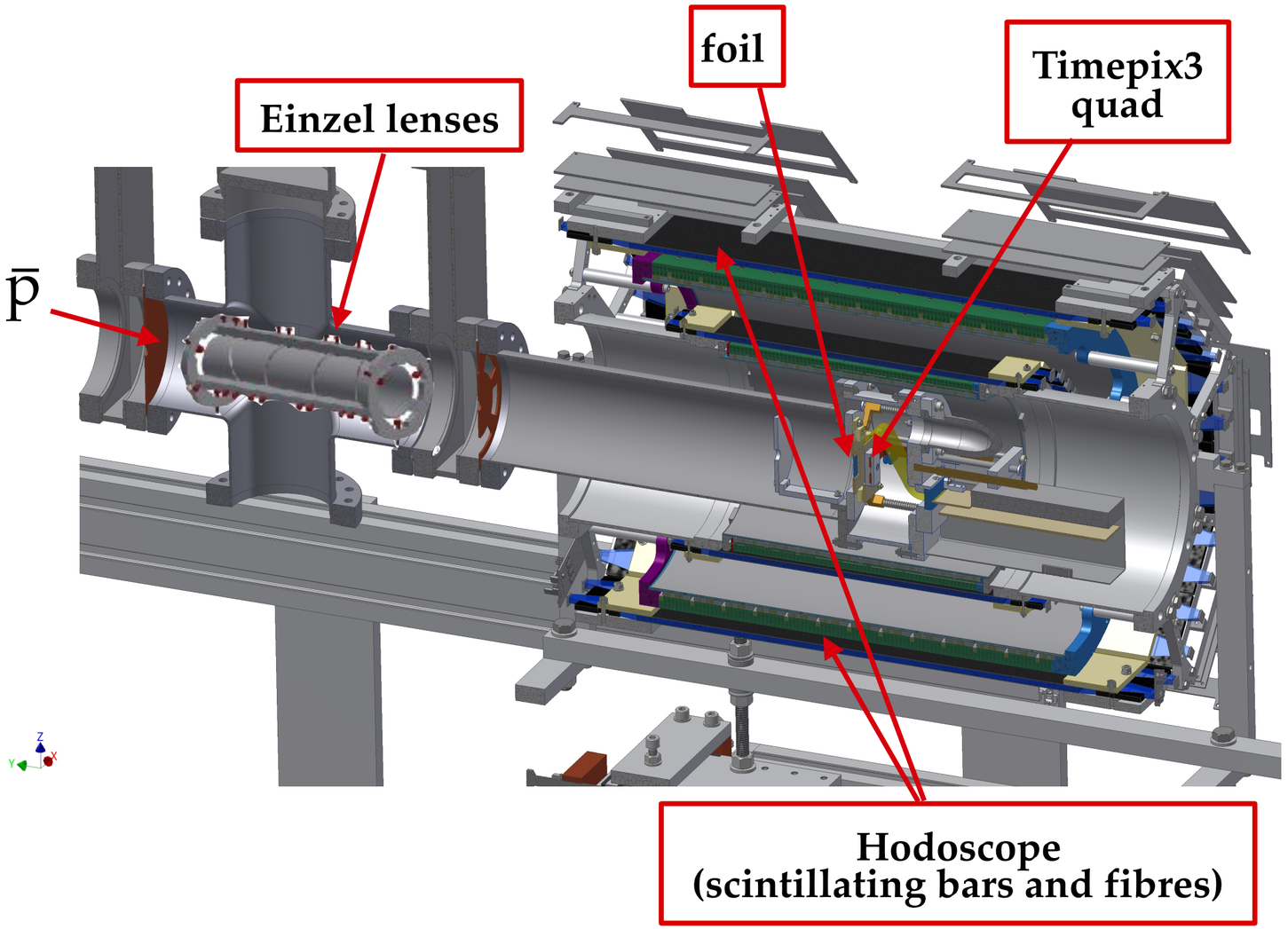
Schematic overview of the measurement

- **The measurement was performed in the ASACUSA apparatus at the AD at CERN.**
- **One spill of antiprotons every 100s from the AD.**
  - **Trapping and slow extraction of 150 eV antiprotons from the MUSASHI.**
    - **Focussing with Einzel lenses.**
    - **Annihilate on the 20 x 20 mm² foil, 2 µm thick (1000 V applied on the foil).**

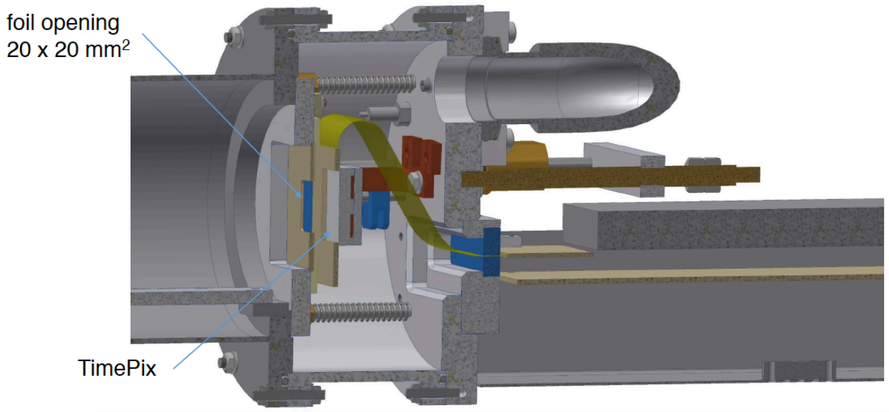


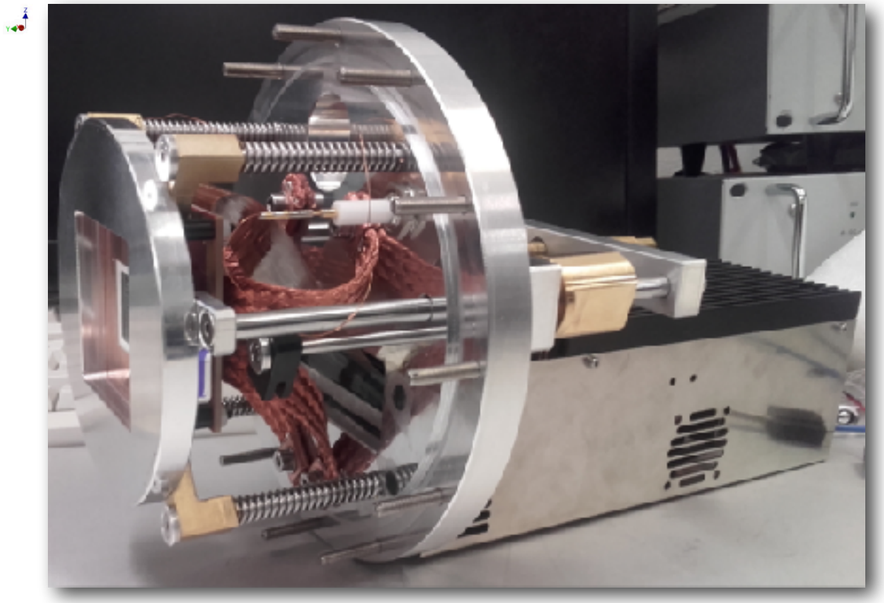
Set-up for the measurement

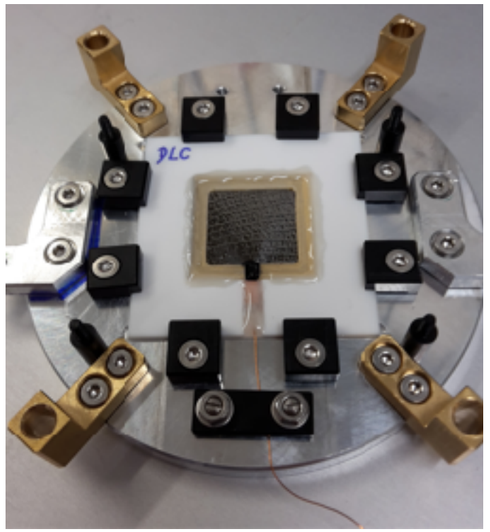
- After annihilation in the foil, the annihilation prongs are detected with two detectors:
  - Timepix3 quad (placed 1 cm away from the foil).
  - Hodoscope (around the foil).
- Detection of:
  - pions (Hodoscope, Timepix3),
  - protons, heavy fragments, gamma (Timepix3).
- Systematic data for ^{6}C, ^{42}Mo, ^{79}Au.

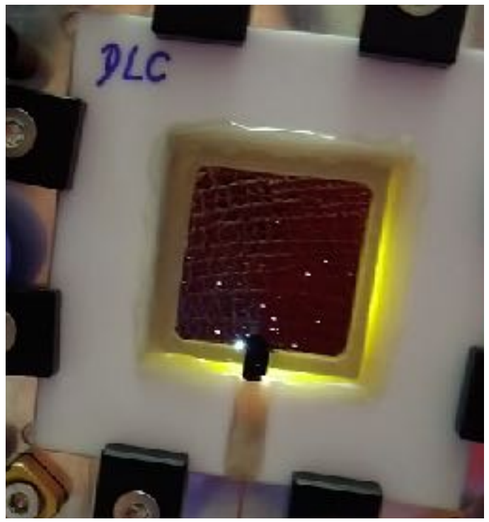


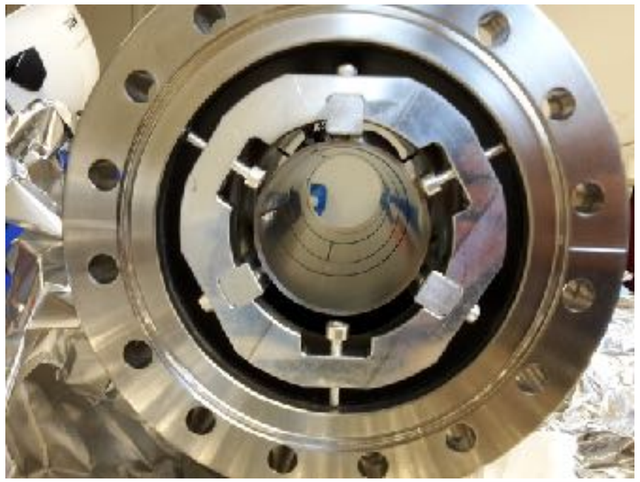
Timepix3 set-up

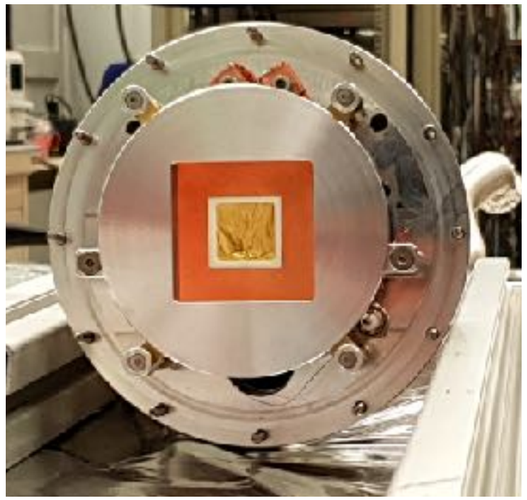








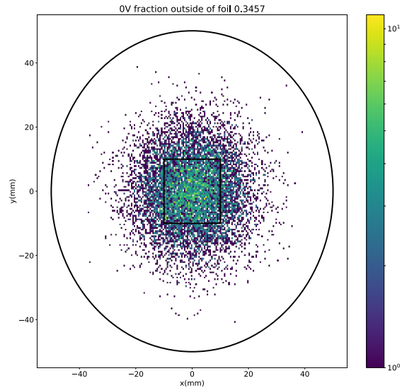




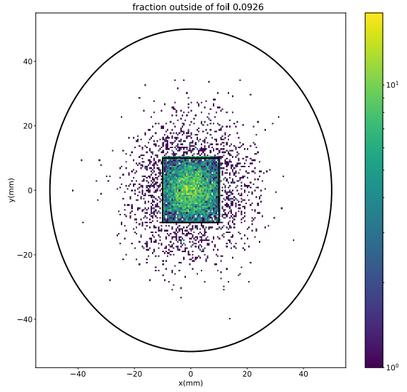
Annihilations on the foil/foil frame

- **Simulations run in SIMION 8.0:**
- **10,000 pbar for each voltage.**
- **150 eV (spread of 1 eV FWHM).**
  - **3D gaussian distribution.**
  - **FWHM 25 mm in X and Y.**
  - **400 mm away from the foil.**

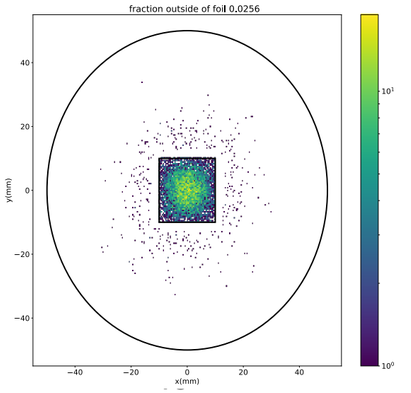
0 V: ~35% outside



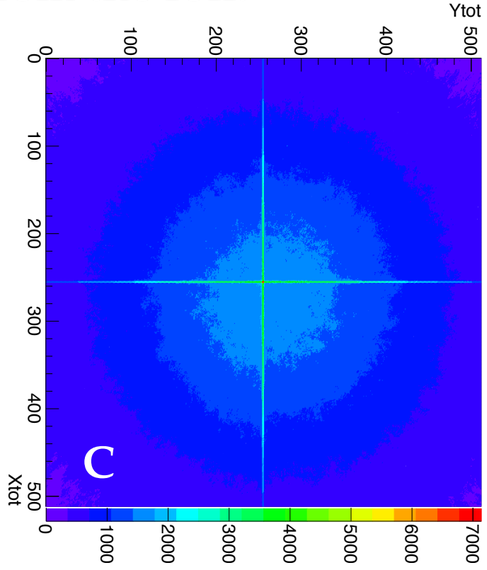
500 V: ~9.3% outside

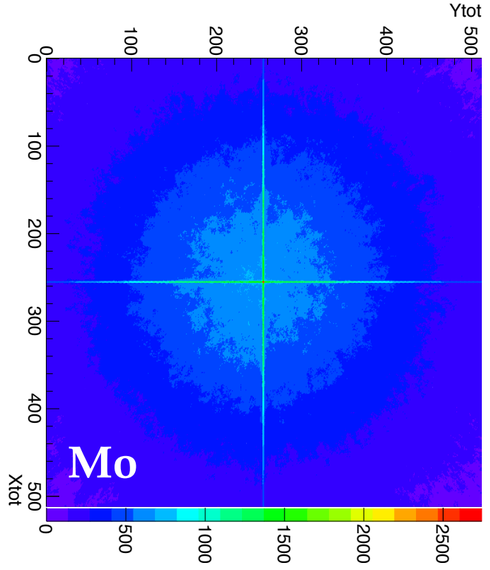


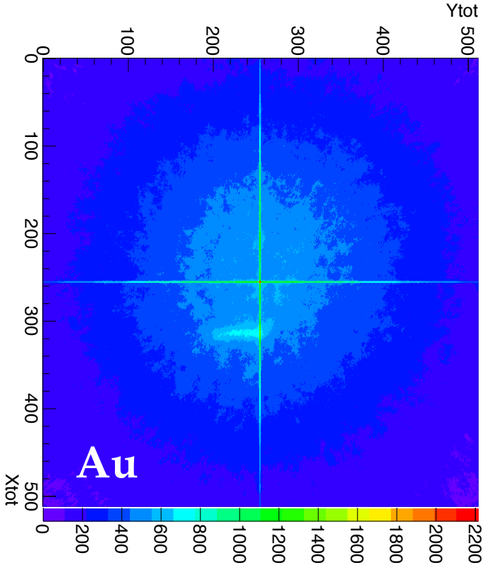
1000 V: ~2.6% outside



Annihilations prongs on Timepix3 (all runs)

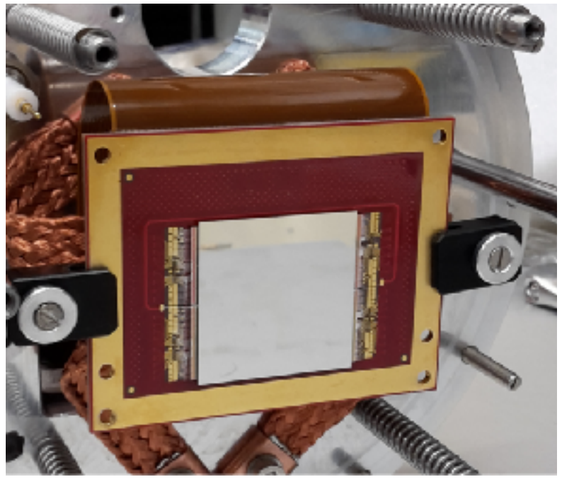


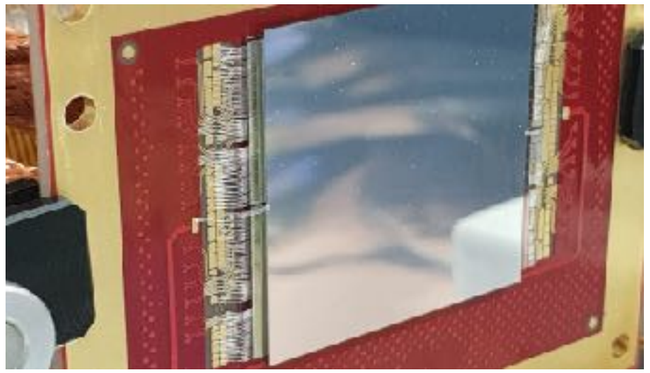


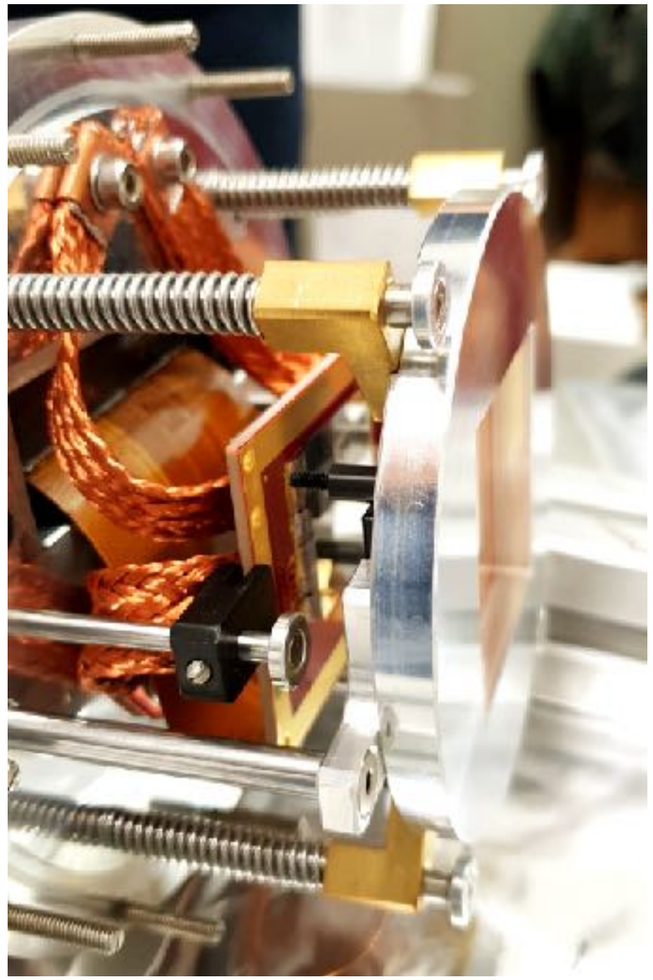


Timepix3 quad

- Timepix3:
  - Developed by the Medipix3 collaboration (CERN)
  - 55 µm pixel pitch.
  - 256 x 256 pixels; active area: 14x14 mm^2.
  - Simultaneous measurement of ToT (Time over Threshold) and ToA (Time of Arrival).
    - Time resolution of 1.6 ns.
    - Dynamic range: up to ~500 keV/pixel.
- Timepix3 quad in ASACUSA:
  - Bump bonded to a Si sensor, 500 µm thick.
  - 512 x 512 pixels; active area: 28x28 mm^2.
  - SPIDR R/O developed by NIKHEF.

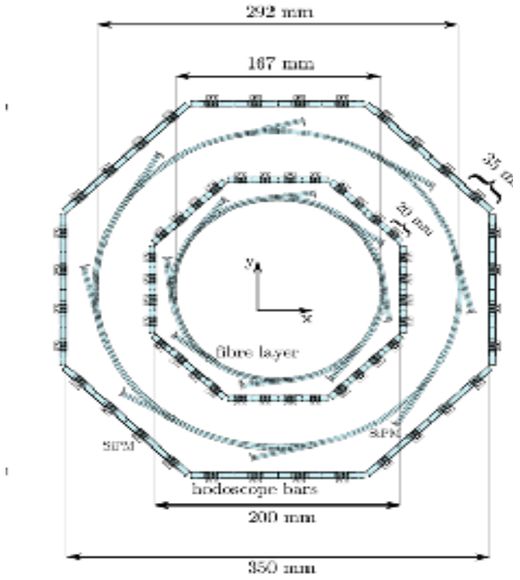


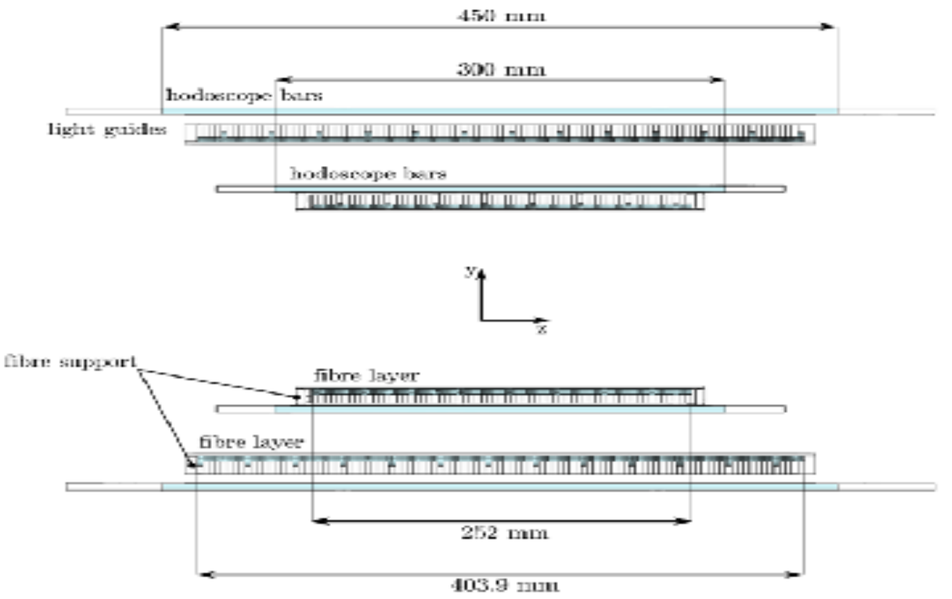


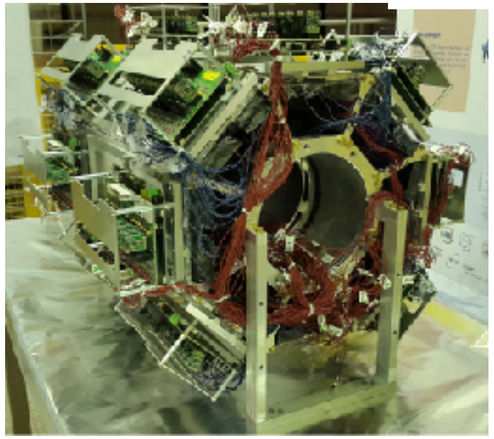


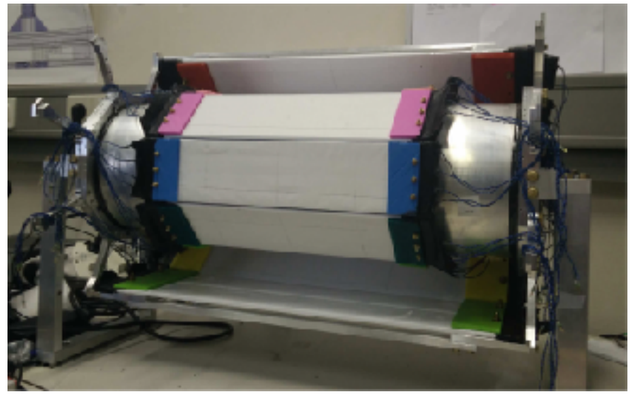
Hodoscope

- Scintillating bars and fibres.
  - 2 layers of bars:
    - 32 plastic scintillating bars per layer.
      - SiPM readout on both sides.
  - 2 layers of fibres:
    - Inner: 63 channels.
    - Outer: 100 channels.
    - Channel: four 2 mm×2 mm fibres glued to one SiPM.
- Rough position in beam direction: ~ 3 cm (FWHM).
- Solid angle: ~80%.
- Efficiency: 0.800 ± 0.0111.
- Background rejection 0.9836 ± 0.0031.





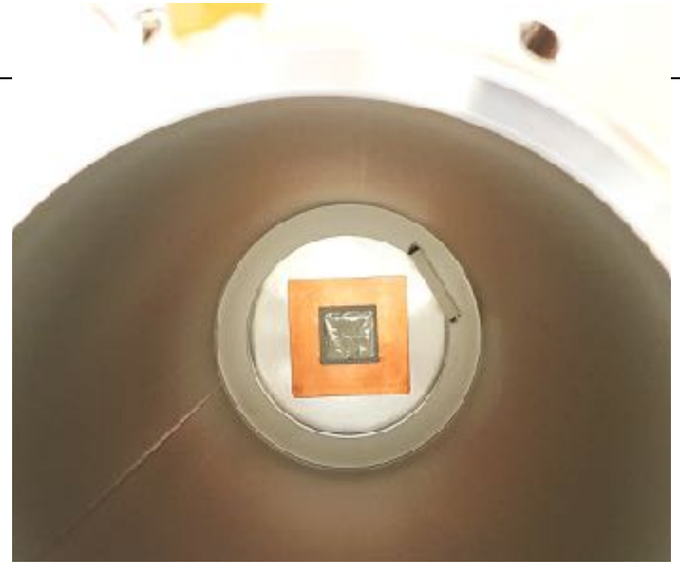


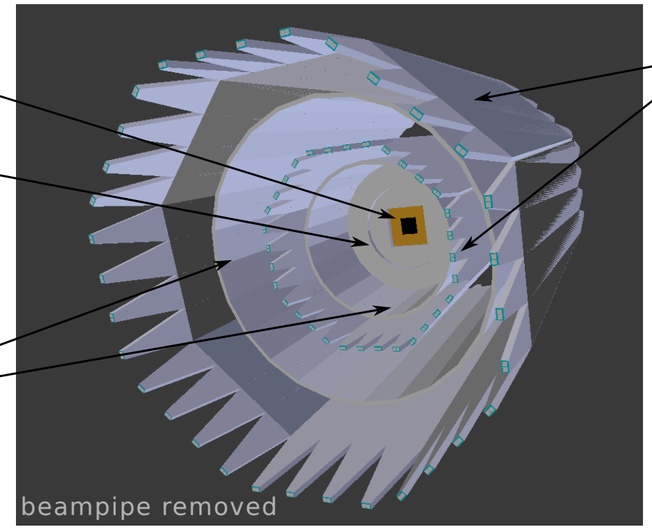


B. Kolbinger, PhD Thesis (2019), Machine Learning for Antihydrogen Detection in ASACUSA"

Simulations

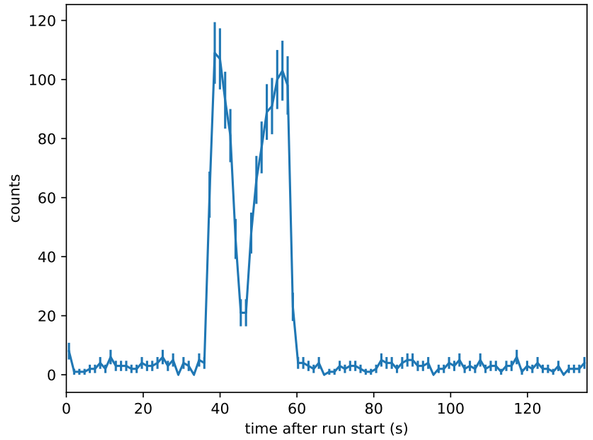
- **GEANT4 - CHIPS and FTFP.**
- **AllPix^2 for digitisation of Timepix3 simulated data (in collaboration with S. Spannagel).**
  - **Electric field.**
  - **Bias.**
  - **Drift of the collected charge.**
- **Not yet included:**
  - **Induced pixel charge.**
  - **Volcano, plasma effect.**
  - **Energy calibration.**
- **Per foil:**
  - **50,000 events simulated for FTFP and for CHIPS.**
  - **~140,00 - 170,000 events in DATA with at least one hit in the Timepix3.**

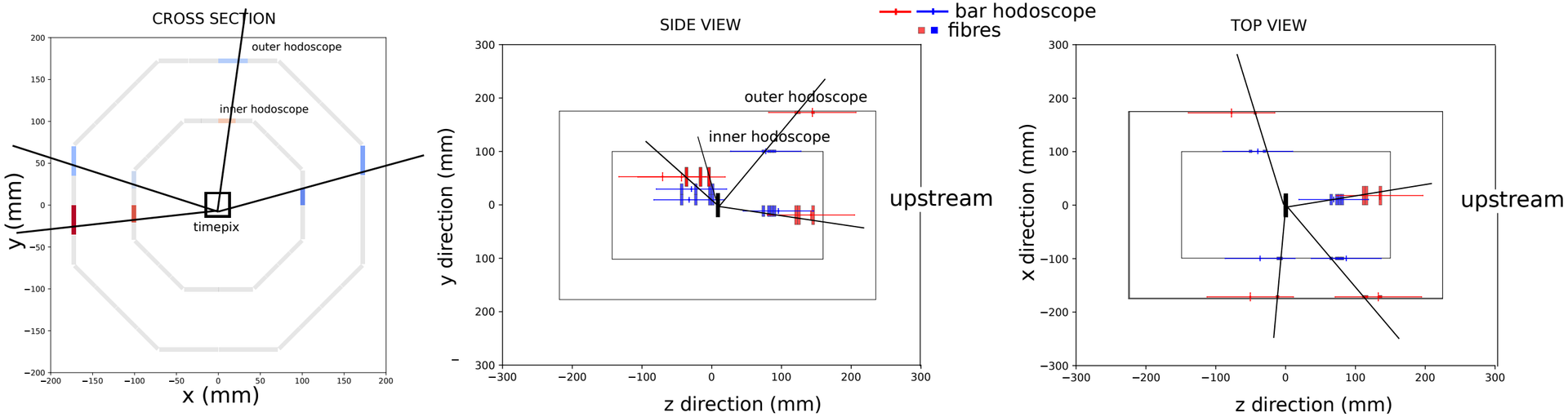




Data analysis in the Hodoscope

- **3D tracking:**
  - **Algorithm developed in the scope of B. Kolbinger PhD thesis.**
- **Cut on time of arrival to reduce BG, no further cuts.**
- **Contribution from the cosmic background: < 1% of total number of antiproton annihilation events.**

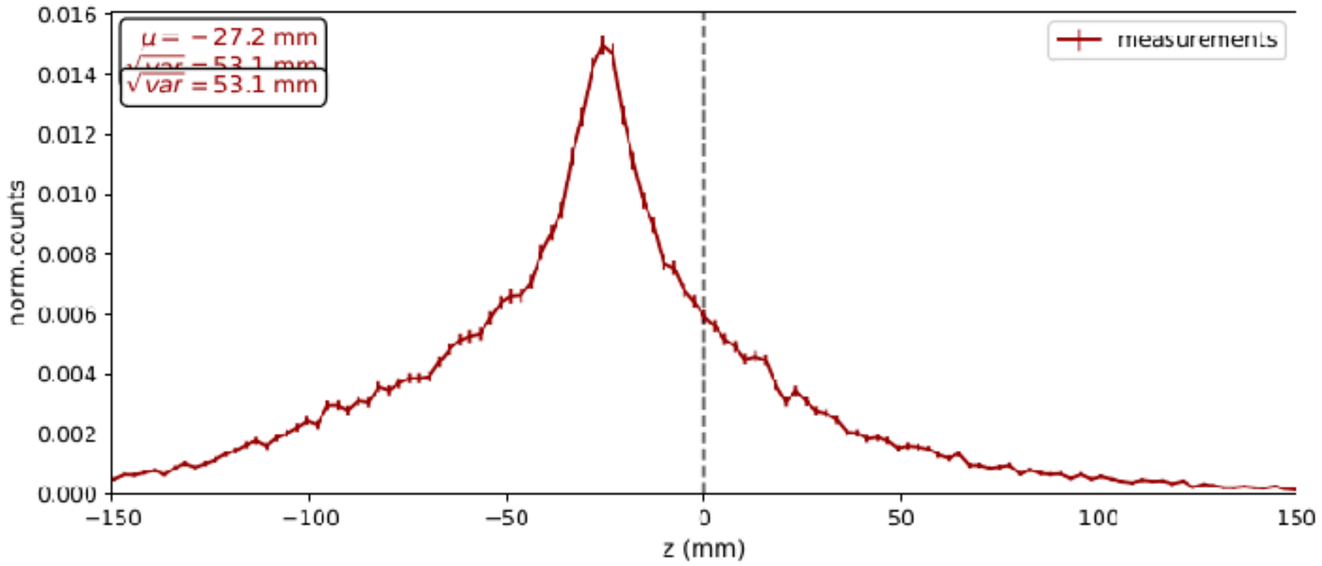


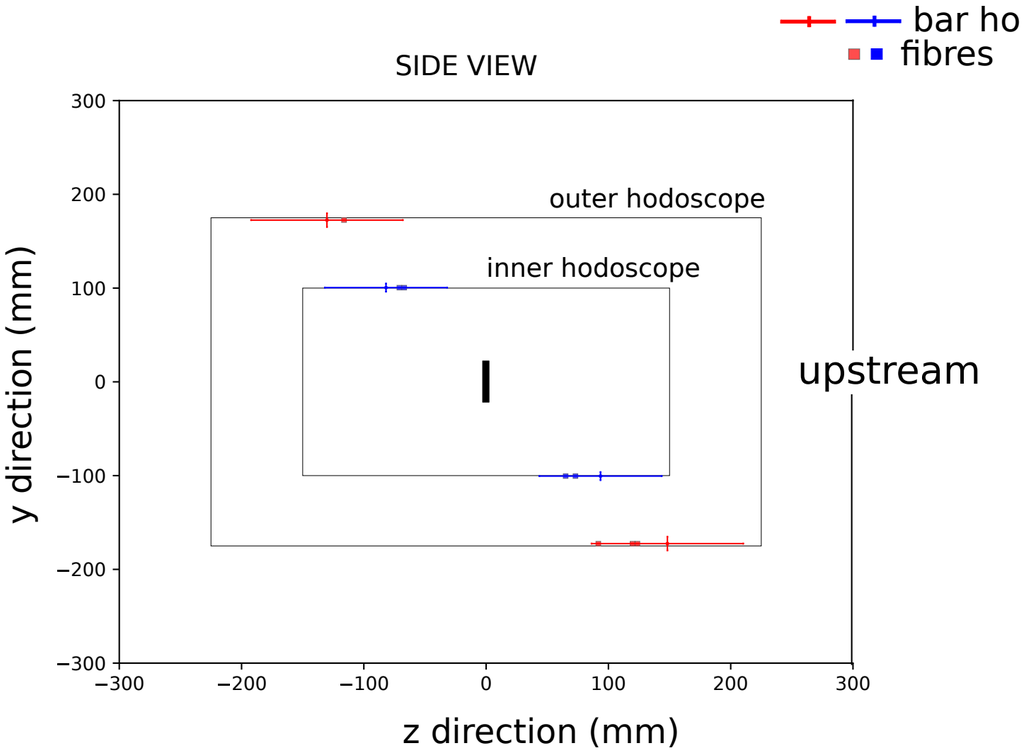


B. Kolbinger, PhD Thesis (2019), Machine Learning for Antihydrogen Detection in ASACUSA"

Reconstructed vertex, z - position

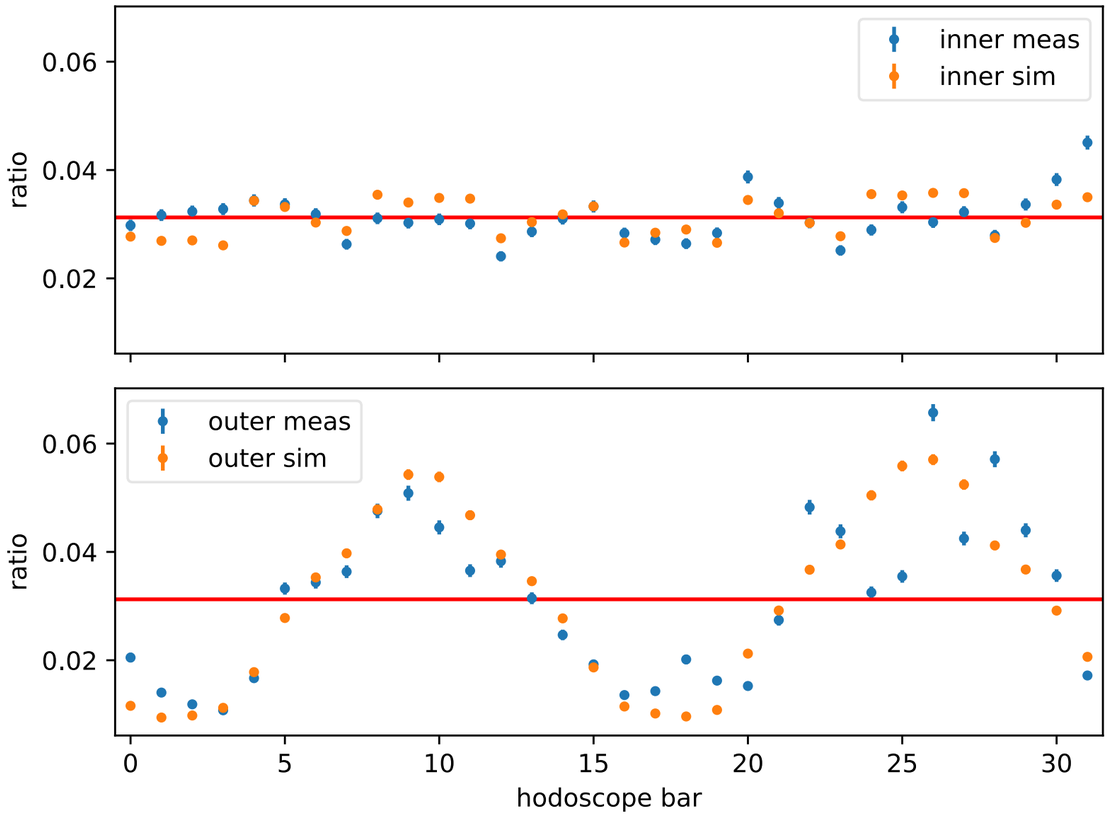
- **z-component of the reconstructed annihilation vertex.**
- **Mo data used for this analysis.**
- **The reconstructed position is used for the simulations.**



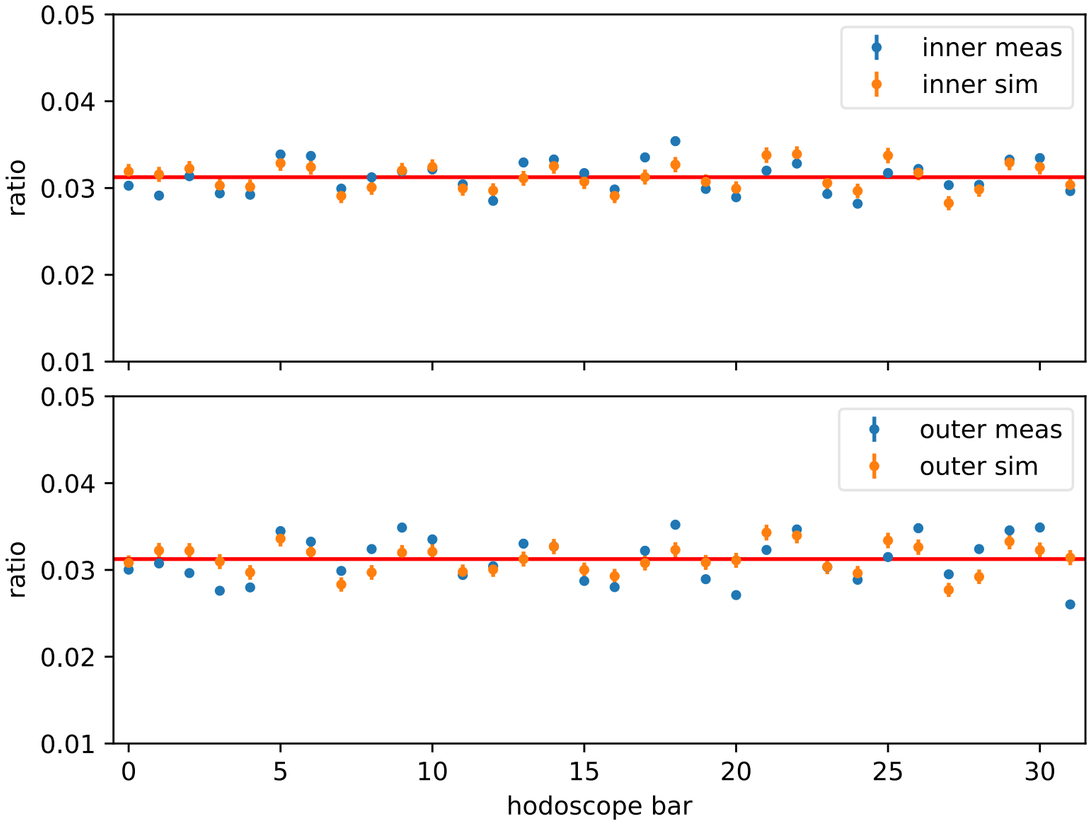


Angular distribution of comics and antiprotons in the Hodoscope

- **Cosmics**

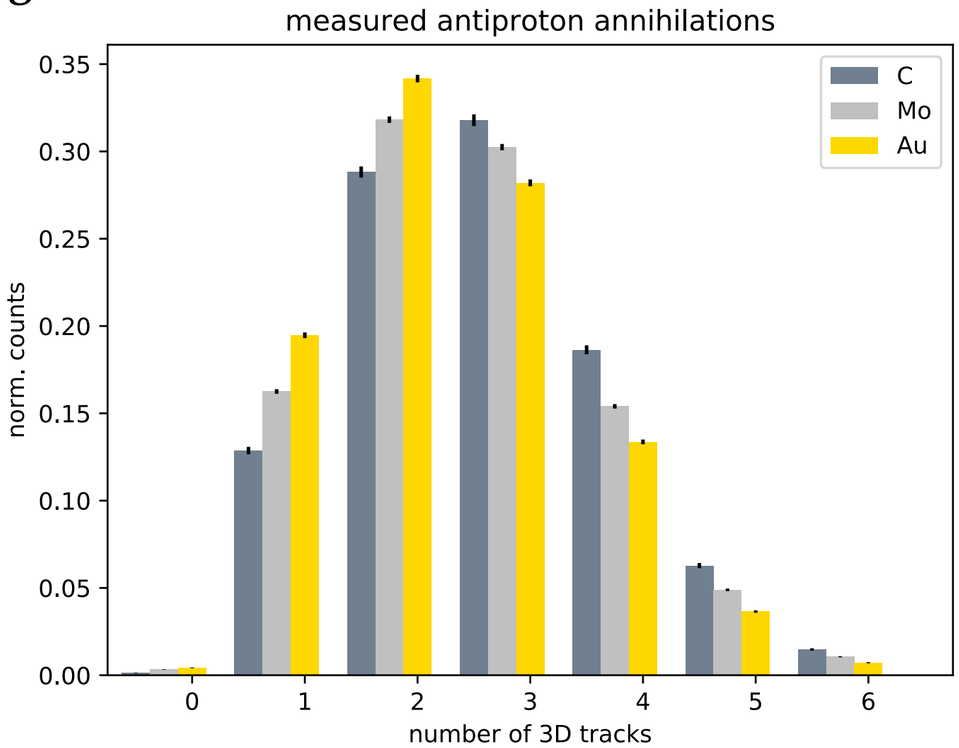


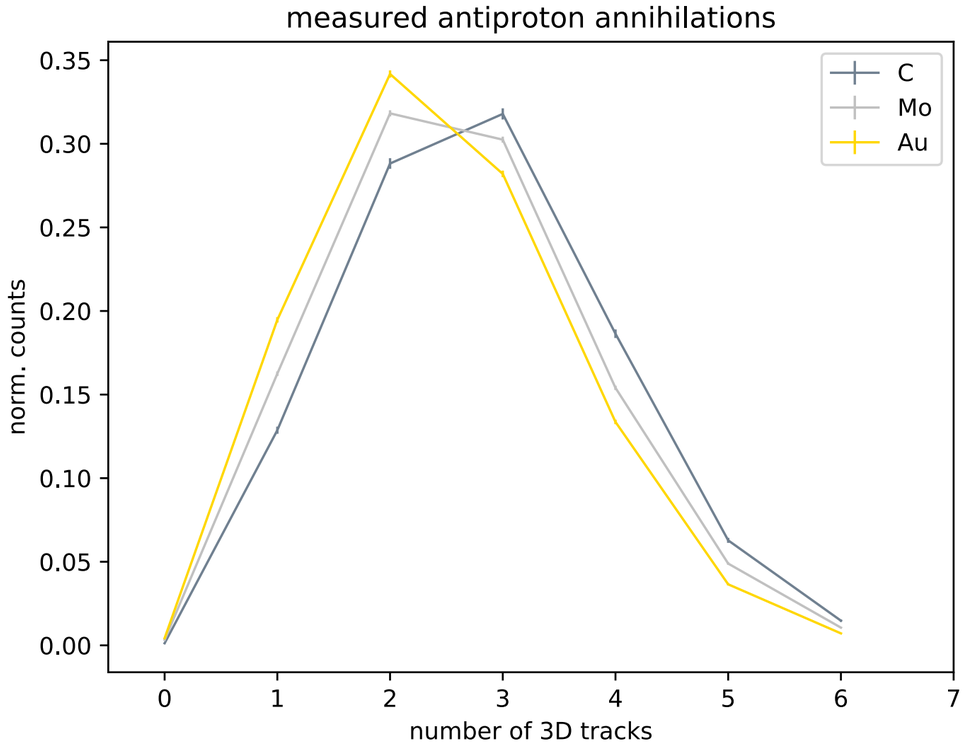
- **Antiprotons**



Reconstructed tracks, DATA

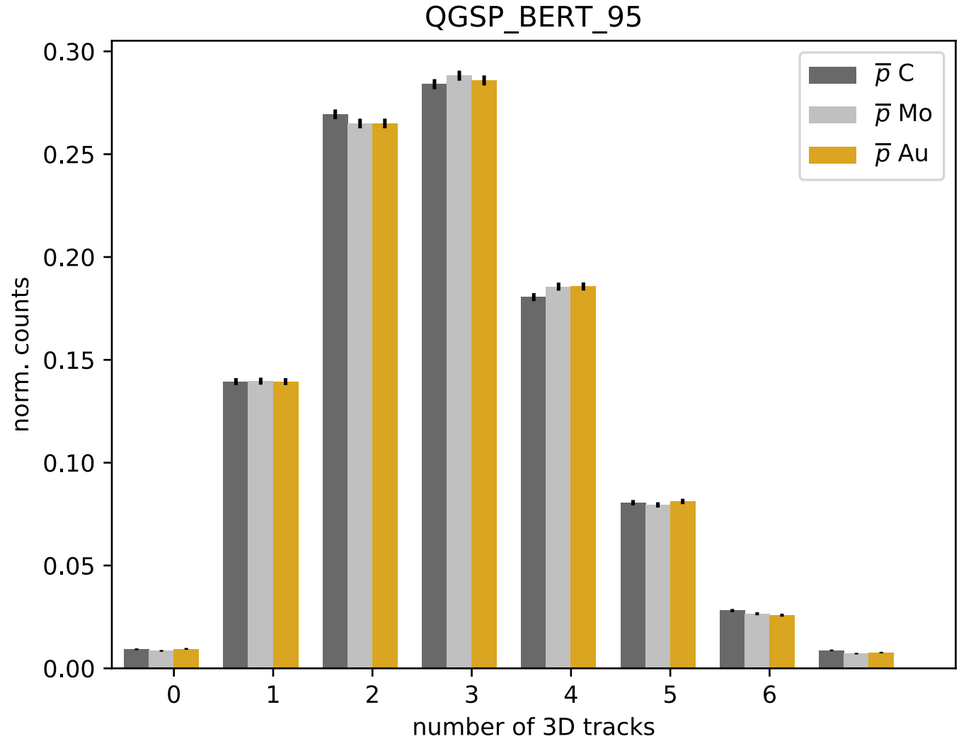
- **Measured antiproton annihilations.**
- **Cut on time of arrival to reduce BG, no further cuts.**
- **Number of tracks = number of detected charged pions.**
- **3D tracking.**

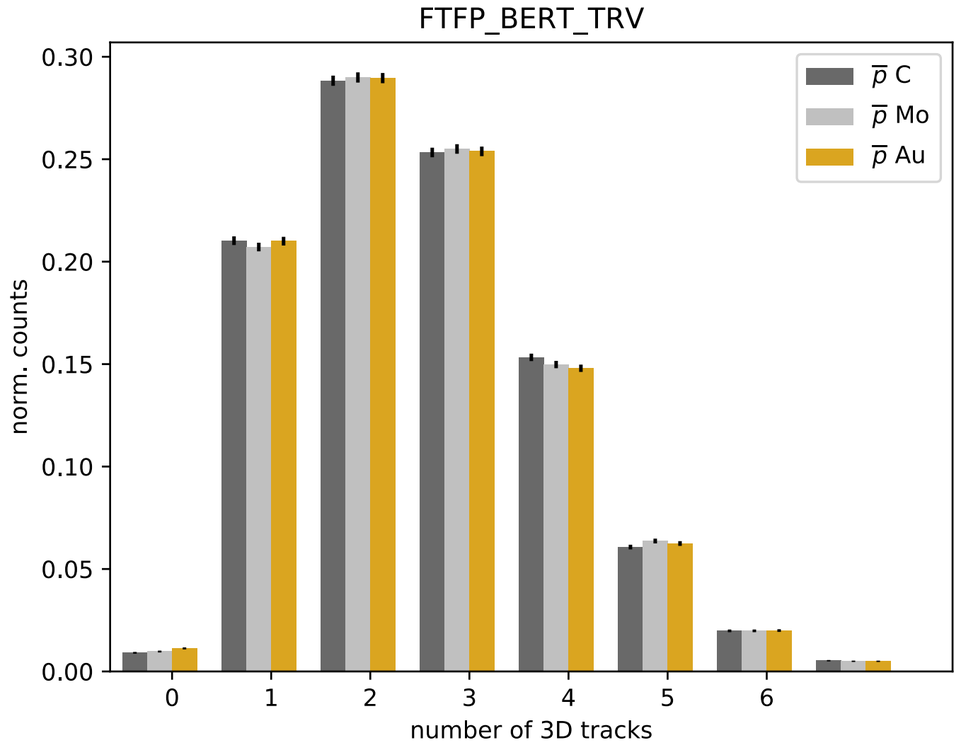




Reconstructed tracks, simulations

- **Simulated antiproton annihilations using FTFP and CHIPS.**
- **#tracks = #detected charged pions in the Hodoscope.**
- **3D tracking.**



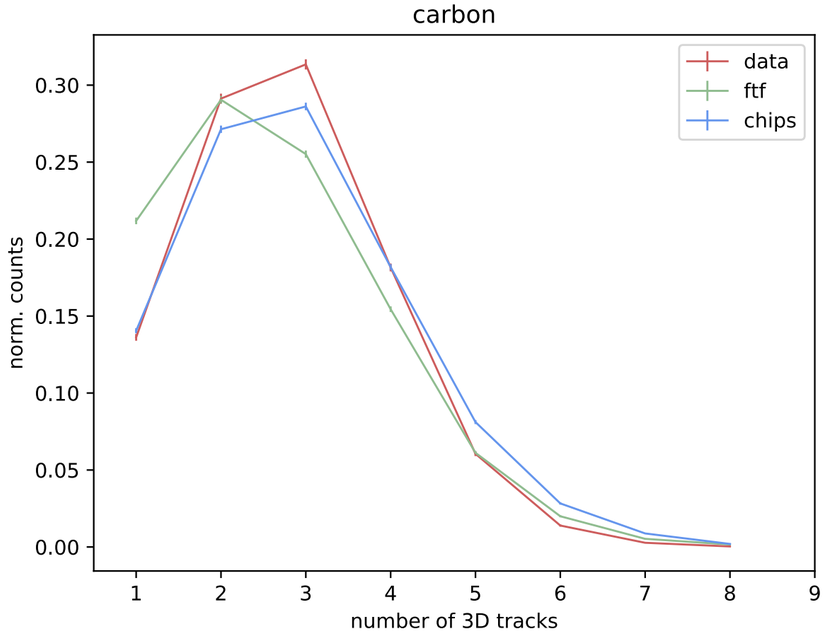


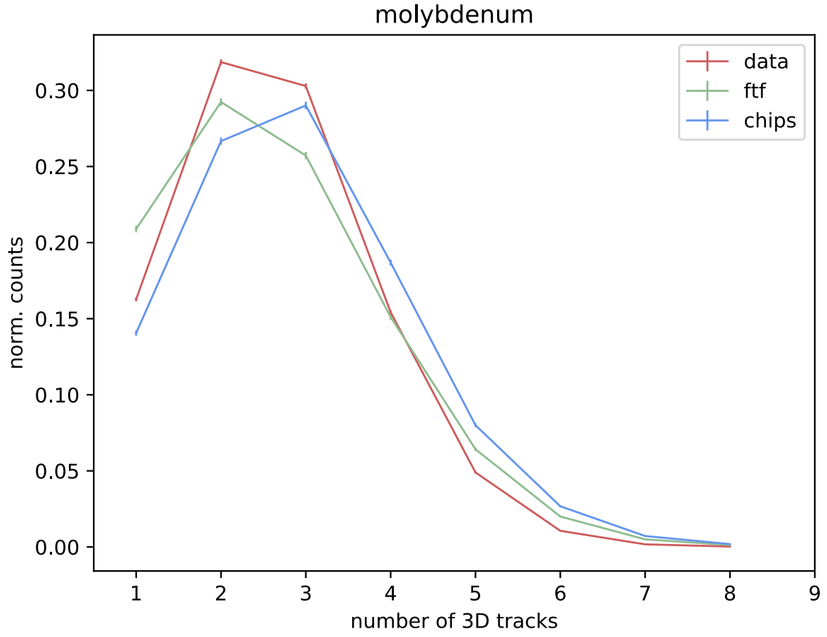
Reconstructed tracks, DATA and simulations

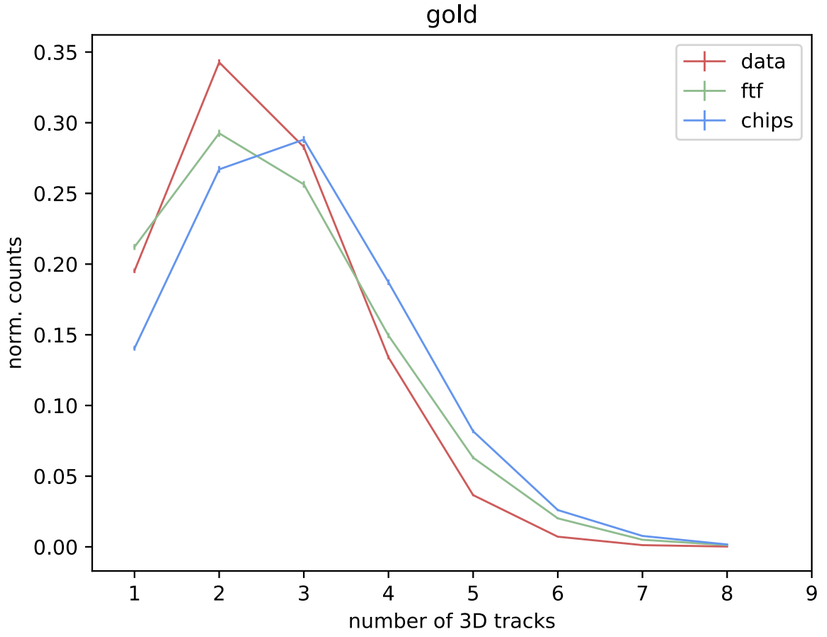
	DATA	FTF	CHIPS
# tracks	2.79±1.19	2.63±1.34	2.90±1.36

	DATA	FTF	CHIPS
# tracks	2.64±1.16	2.63±1.33	2.90±1.35

	DATA	FTF	CHIPS
# tracks	2.49±1.13	2.62±1.34	2.89±1.35

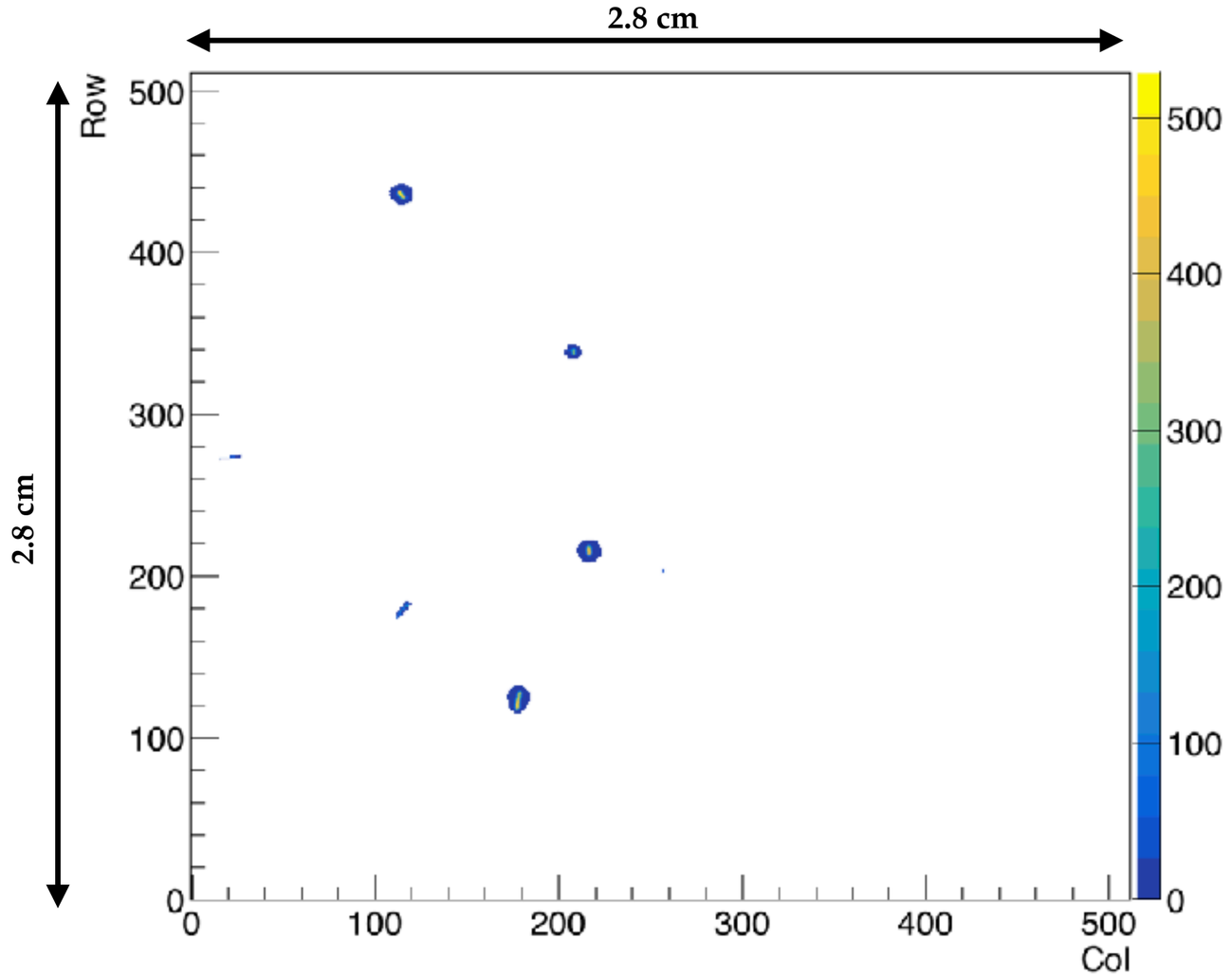






Annihilation event in Timepix3, DATA

- **Trigger from the Hodoscope** (coincidence inner+outer layer) -> timestamped in the Timepix3.
- **Time window for event** = ±**1 μs** [±5 μs < 0.5% difference in the #clusters/event].
- **Hitmap for event** - 512 x 512 matrix of the quad.
- Only data associated with a time stamped trigger from the Hodoscope are included in the analysis.



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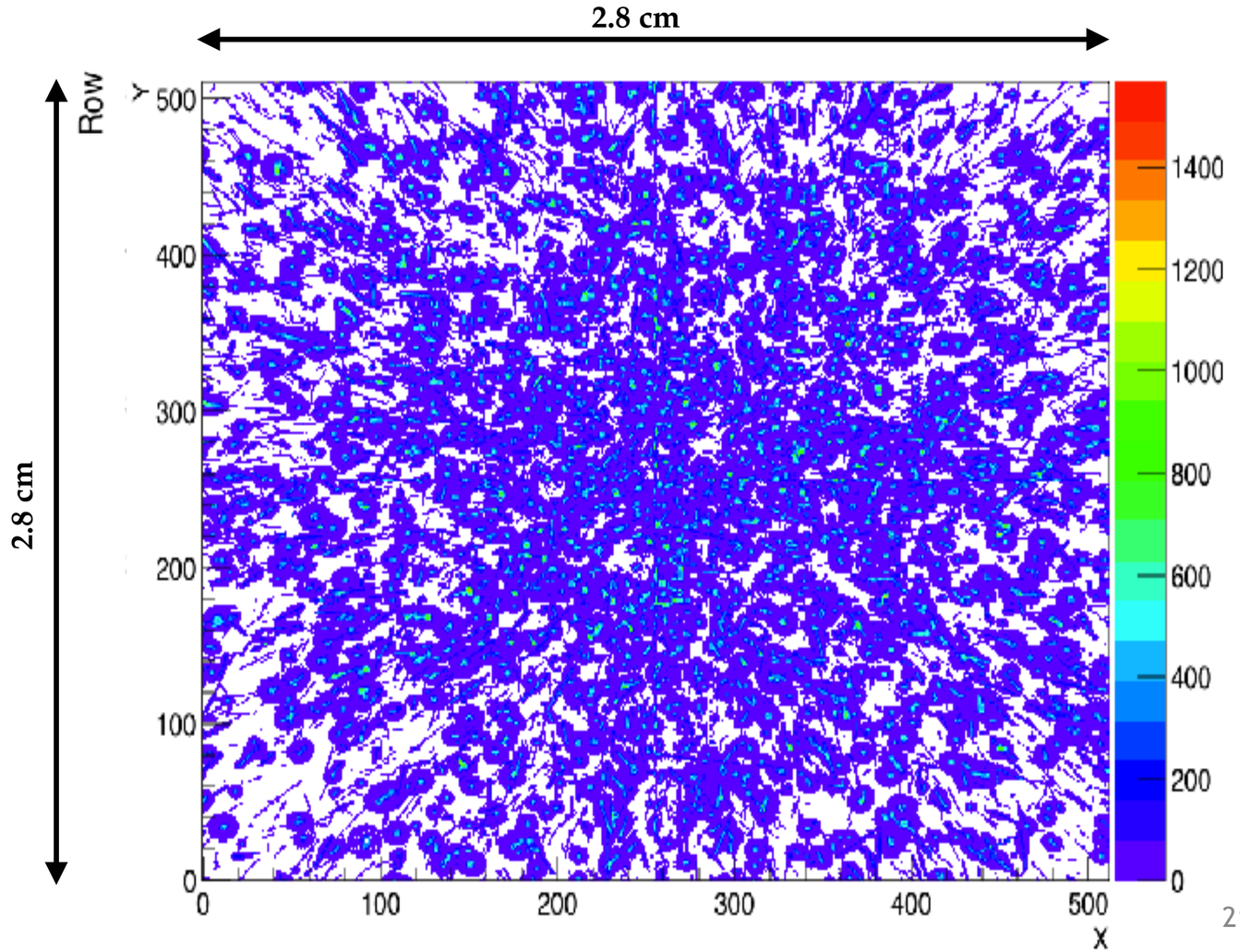
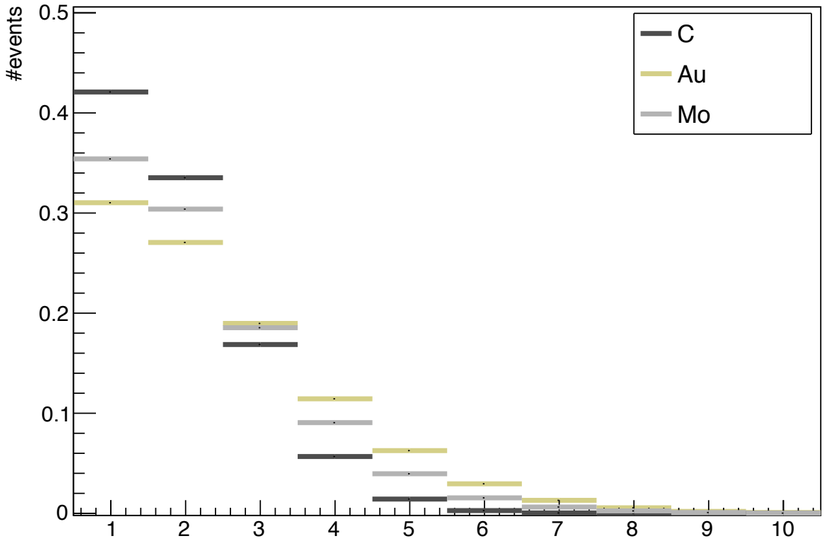
- **Hitmap for event** - 512 x 512 matrix of the quad.
- Only data associated with a time stamped trigger from the Hodoscope are included in the analysis.



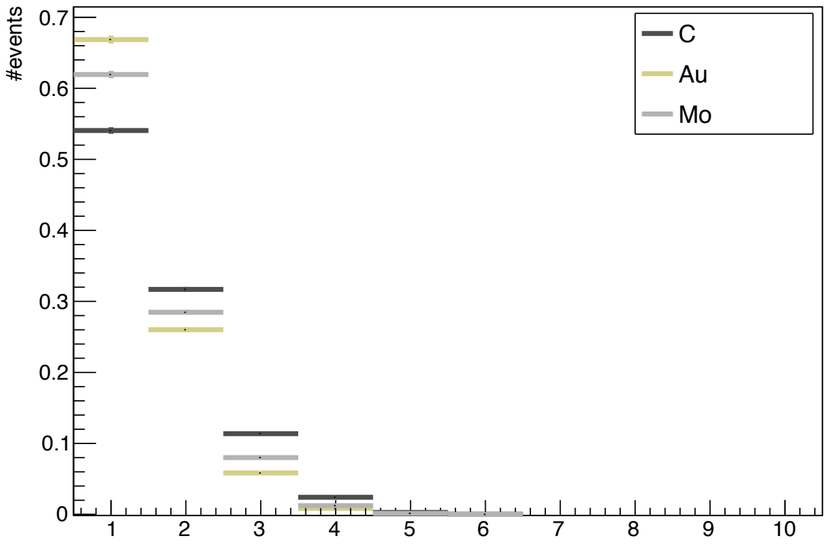
Number of clusters per event (particles detected in Timepix3)

- #clusters = charged particles (MIPs+HIPs) detected by the Timepix3.
  - DATA: lower Z, higher probability for 1 (or 2) prongs.
  - GEANT4 (FTFP/CHIPS): higher Z, higher probability for 1 (or 2) prongs.

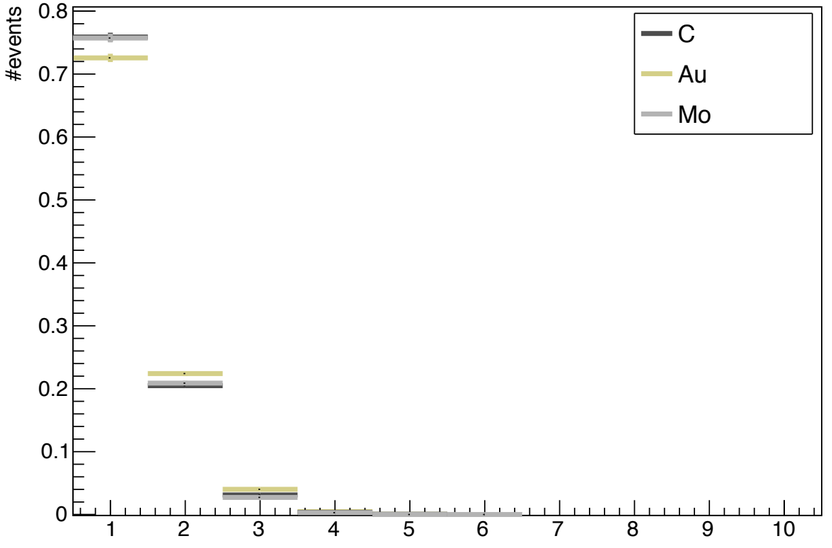
DATA



FTFP



CHIPS



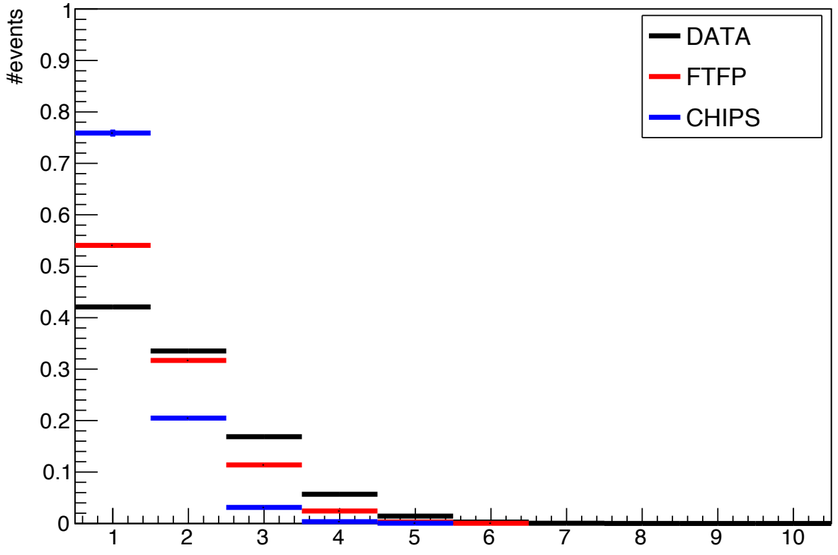
Number of clusters per event (particles detected in Timepix3)

C	DATA	FTF	CHIPS
# events	165,981	25,519	16,126
#clusters	318,083	41,575	20,622
cl./event	1.92±1.0	1.63±0.81	1.28±0.54

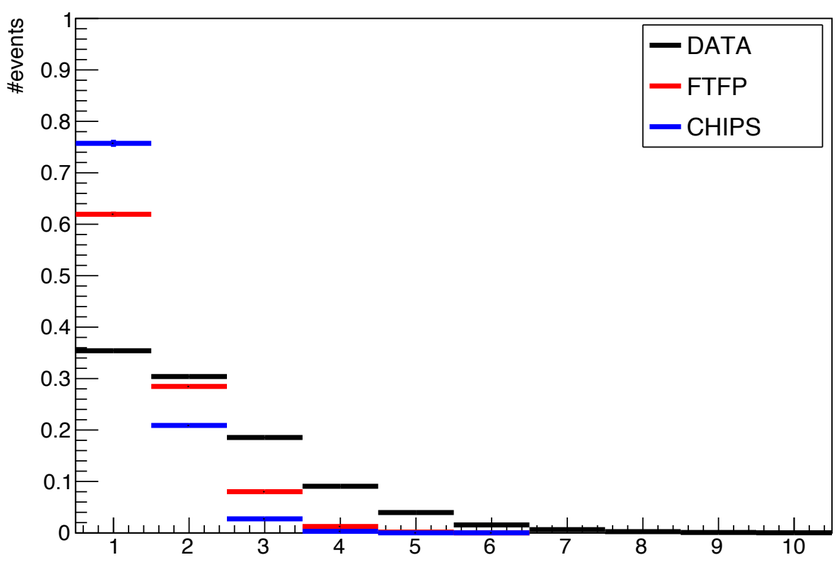
Mo	DATA	FTF	CHIPS
# events	143,793	23,295	16,009
#clusters	323,274	34, 643	20,340
cl./event	2.25±1.32	1.49±0.71	1.28±0.53

Au	DATA	FTF	CHIPS
# events	149,137	20,091	16 ,633
#clusters	378,274	28,194	21,881
cl./event	2.53±1.55	1.41±0.65	1.32±0.58

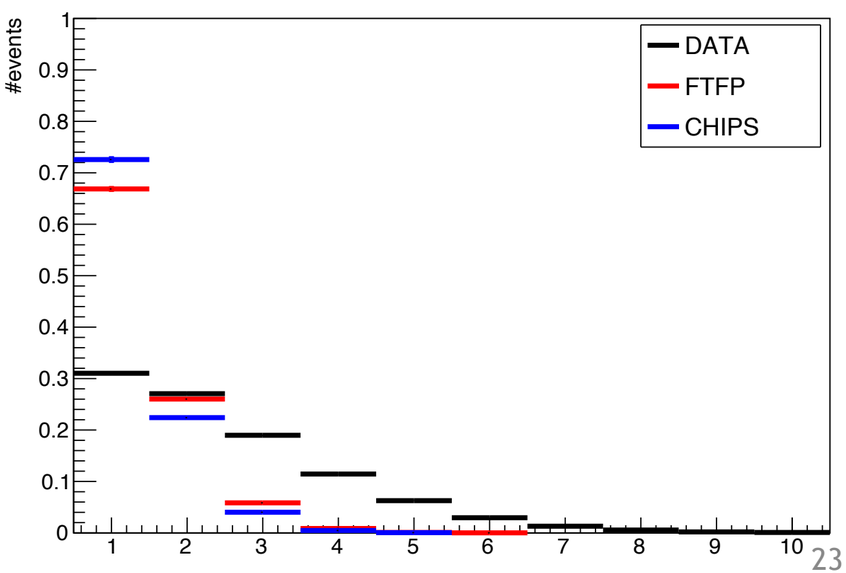
C



Mo

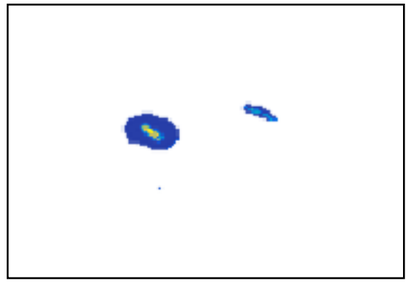


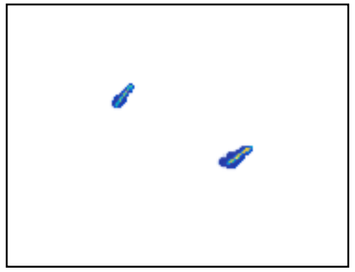
Au



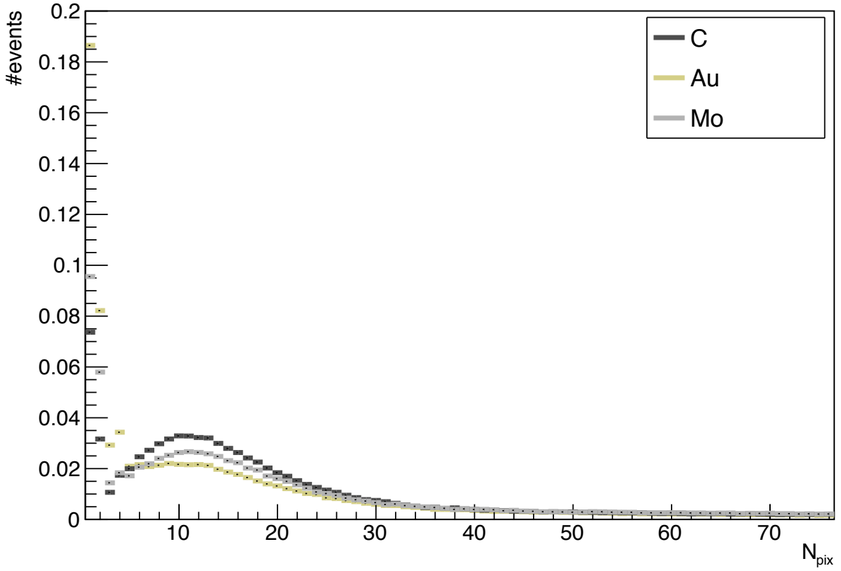
Cluster size

- **Size of the clusters from prongs detected in Timepix3.**
  - **In simulations: dependent on the digitisation model.**
  - **Effects like induced pixels, plasma/volcano effects not yet included in the digitisation.**

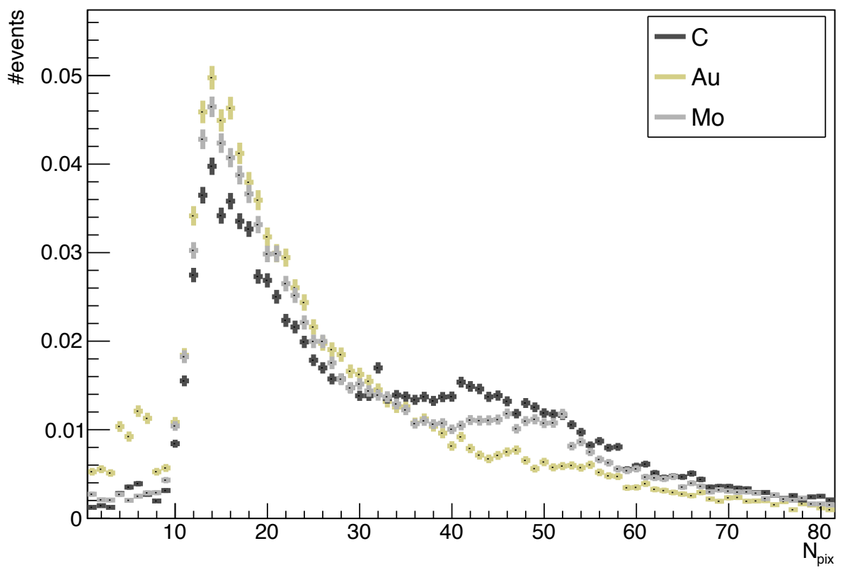




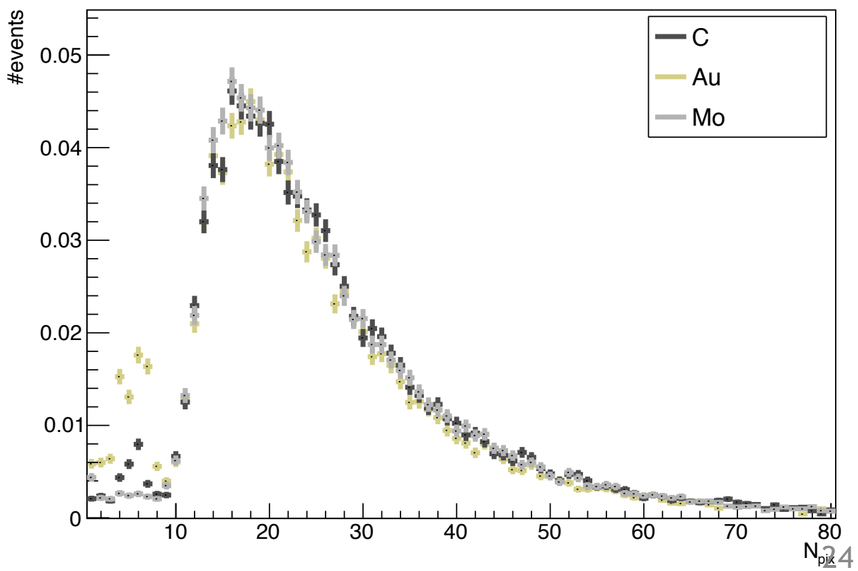
DATA



FTFP



CHIPS



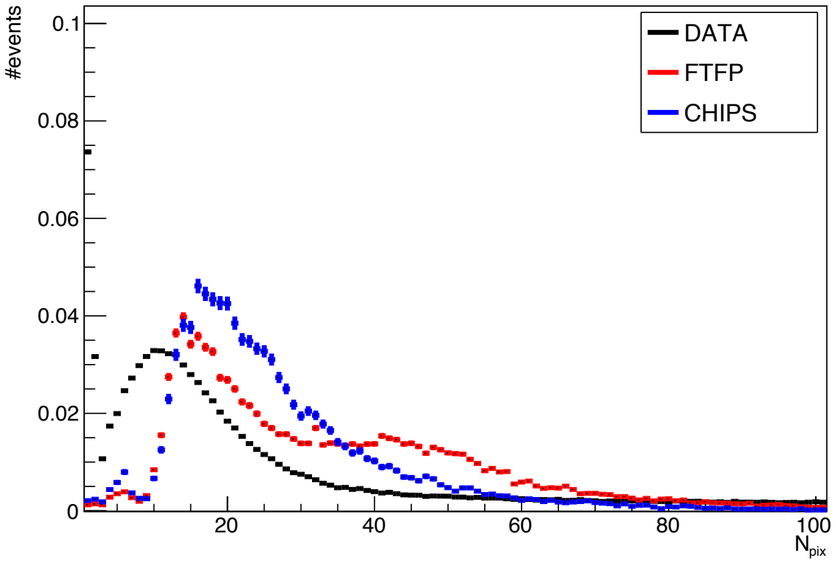
Cluster size

C	DATA	FTF	CHIPS
1pix cl.	7.4 %	0.12 %	0.21 %
mean cl. size	40.71	34.65	27.44

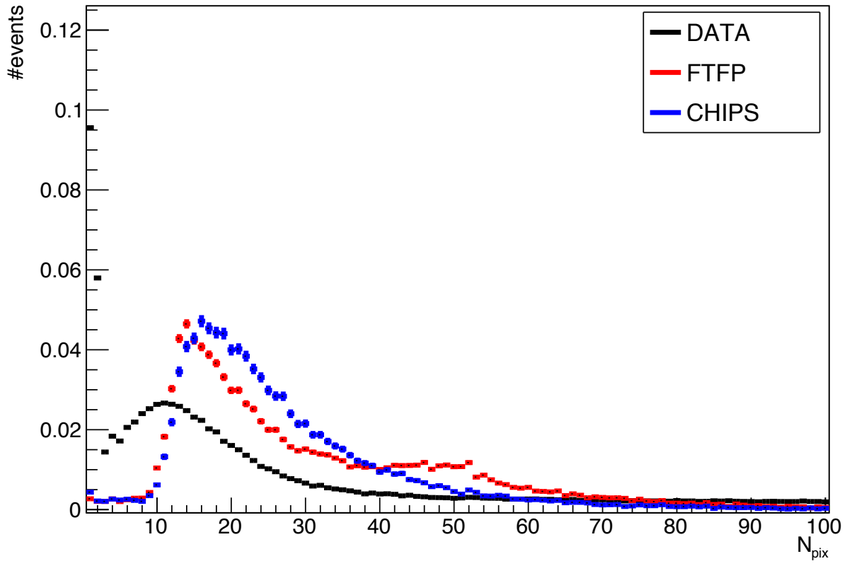
Mo	DATA	FTF	CHIPS
1pix cl.	9.5 %	0.27 %	0.44 %
mean cl. size	44.91	31.81	27.81

Au	DATA	FTF	CHIPS
1pix cl.	18.7 %	0.52 %	0.58 %
mean cl. size	37.47	28.01	25.86

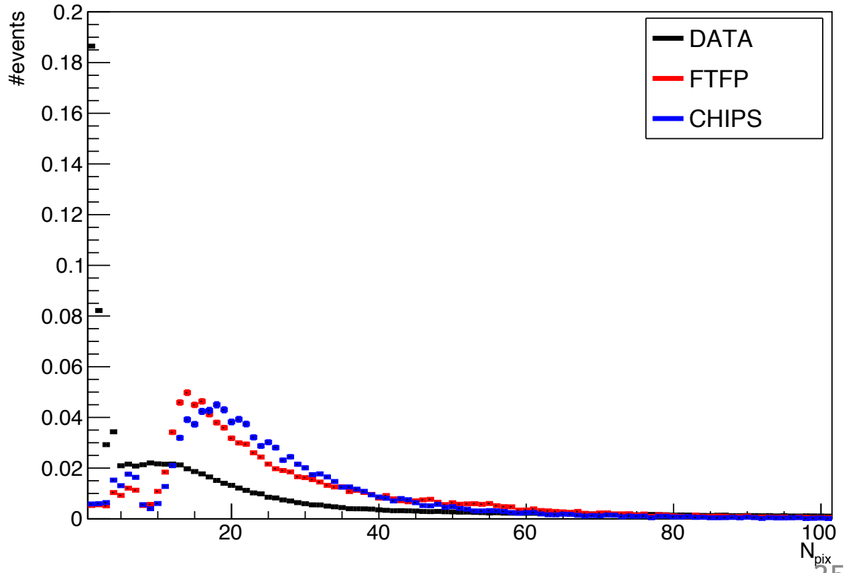
C



Mo

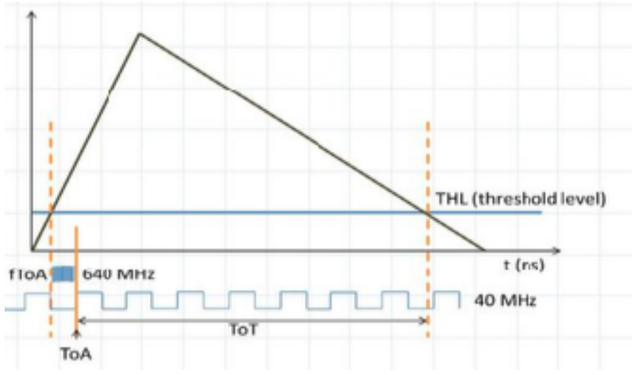


Au

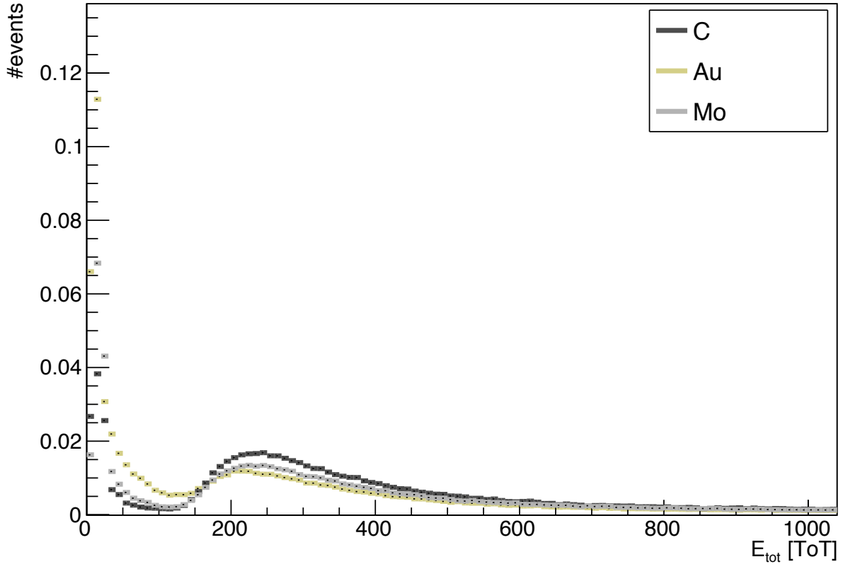


Energy deposited in a cluster: ToT

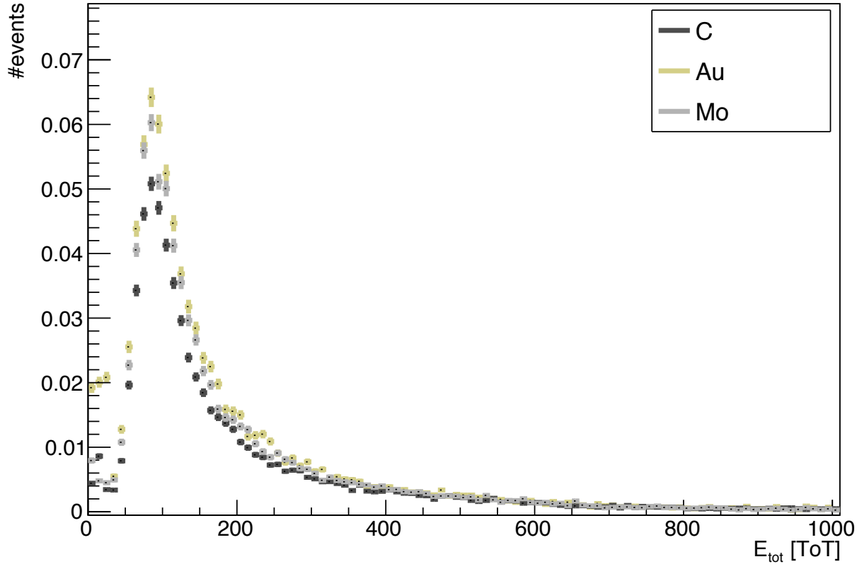
- 40 MHz R/O (ToT).
- 640 MHz fine clock (ToA).
- ToT counts (1 ToT = 25 ns).
- Proportional to deposited energy.



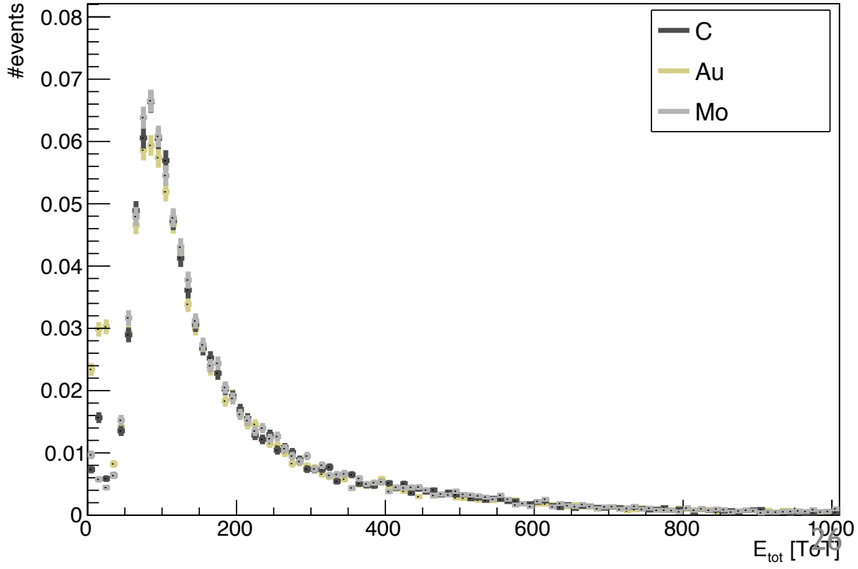
DATA



FTFP

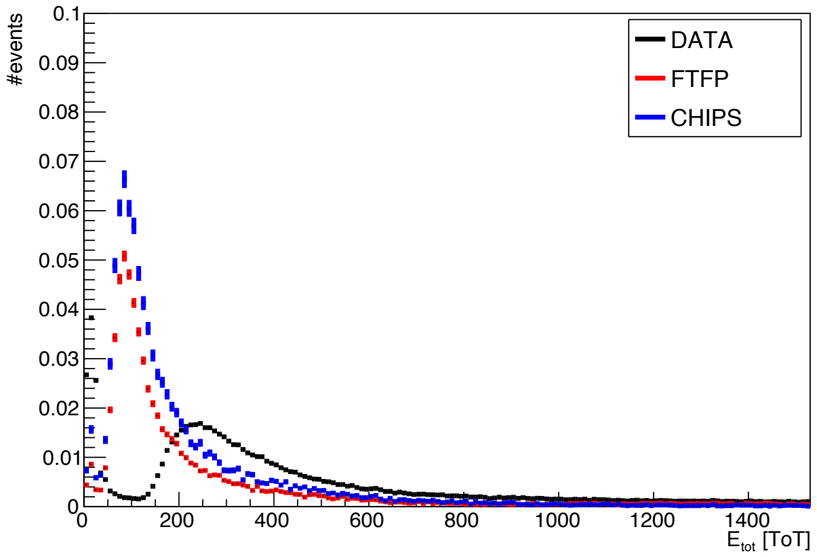


CHIPS

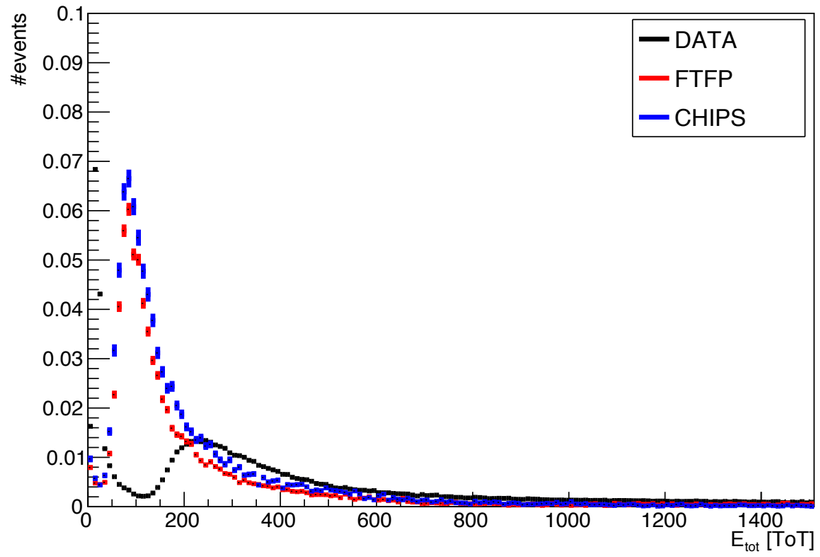


Energy deposited in a cluster: ToT

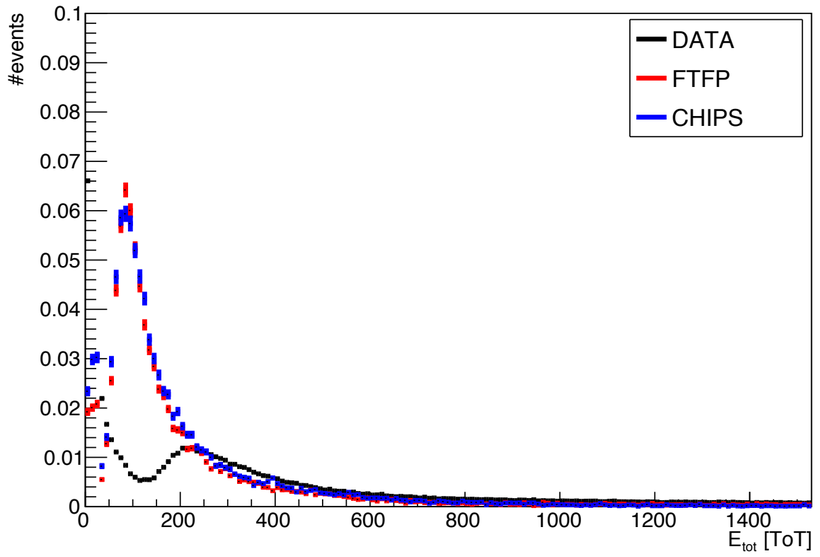
C



Mo

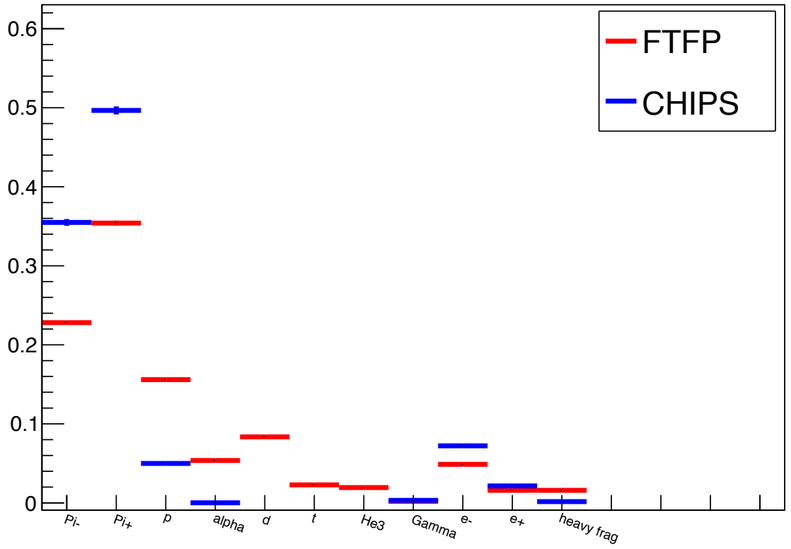


Au

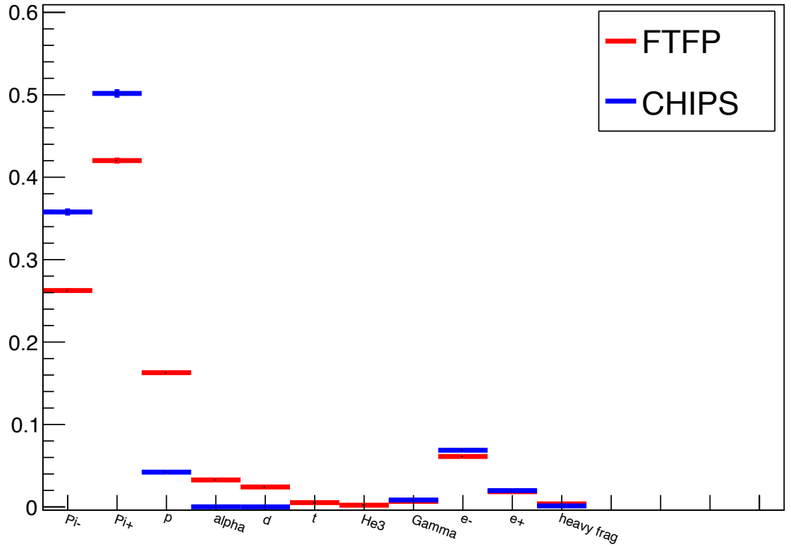


Particle ID, simulations

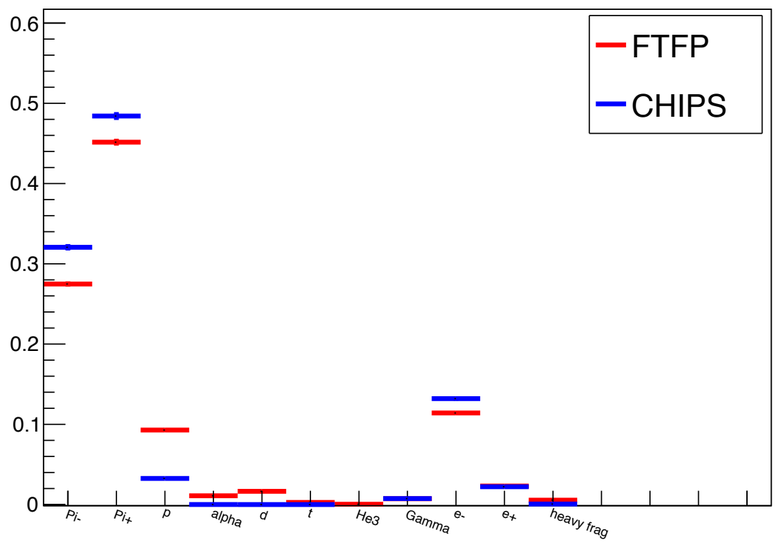
C



Mo



Au

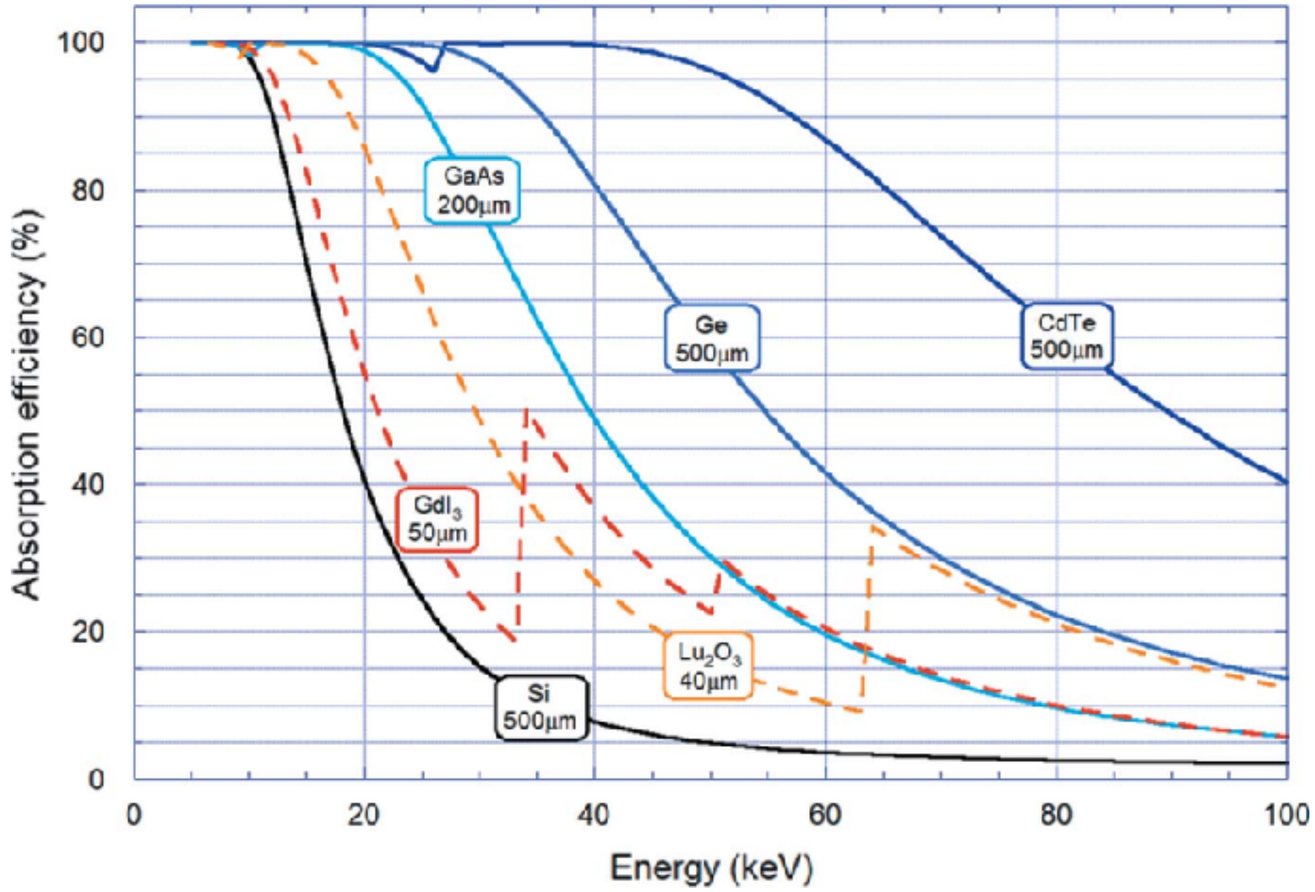


Calibration of Timepix3

- **Test pulse calibration of the deposited energy.**
- **^{241}Am source for verification:**
  - **Data with Al foil on the way (no alphas make it to the detector, only gammas).**

$$^{241}_{95}\mathrm{Am} \xrightarrow{432.2\mathrm{y}} ^{237}_{93}\mathrm{Np} + ^{4}_{2}\alpha^{2+} + \gamma\ 59.5409\ \mathrm{keV}$$

Calculated absorption eff. for 0-100 keV photons



Data with ^{241}Am source

Am decay:

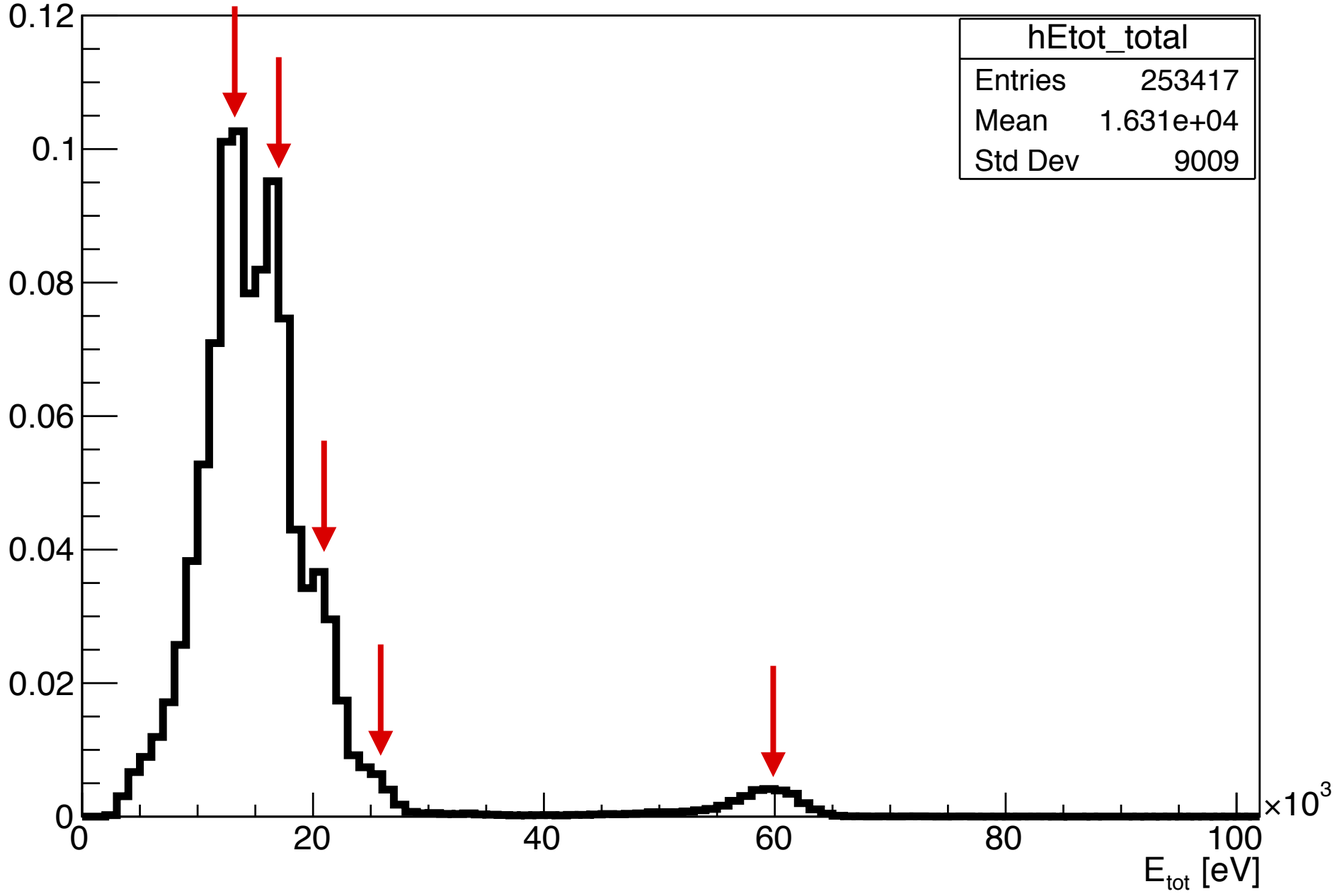
16.6 keV	(37.7%).
59.5 keV	(35.9%)
26.34 keV	(2.4%)
33.2 keV	(0.12%)
43.4 keV	(0.07%)

Np decay:

13.9 keV
17.7 keV
20.7 keV

Sigma of the 59.5 keV peak -> 2.4 keV

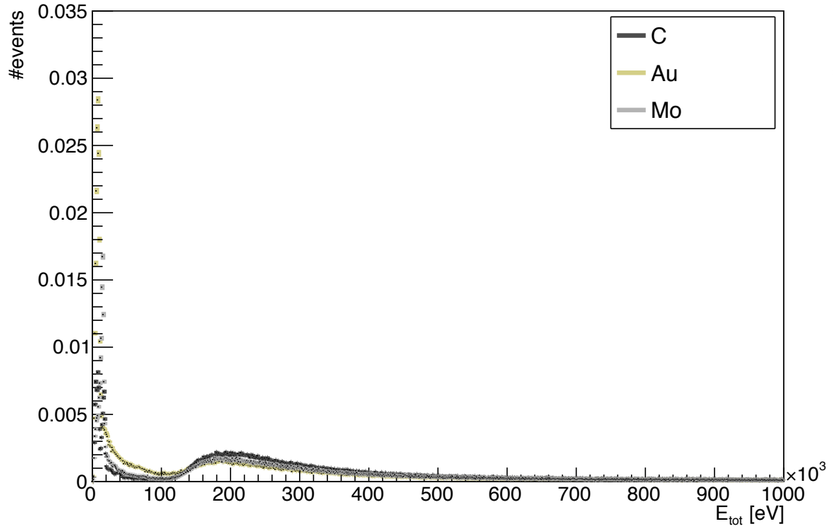
Total energy deposited from all clusters from ^{241}Am



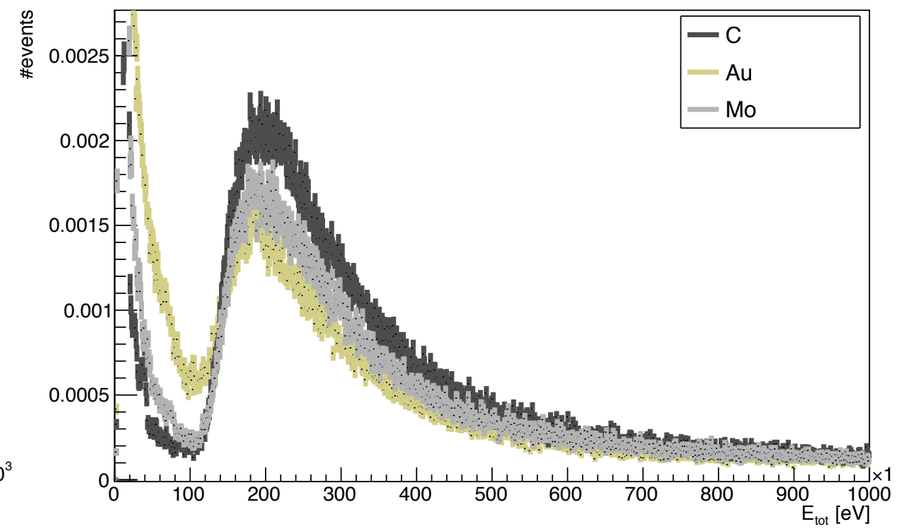
Energy deposited in a cluster, DATA

- **Pions are MIPs -> ~ 0.3 keV/um in Si;**
- **~200 keV, compatible with the signal from cosmics (MIPs).**
- **Clusters from heavy fragments with deposited energy up to few MeV.**

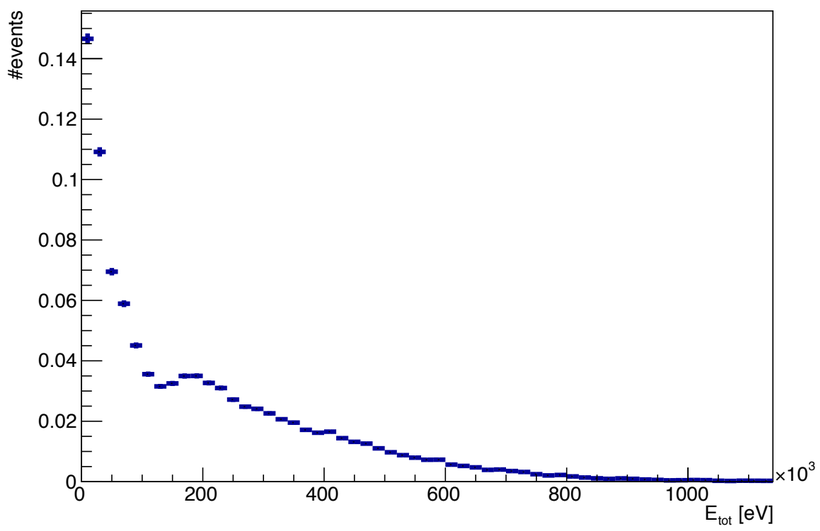
Total energy deposited from all clusters, antiproton annihilations



Total energy deposited from all clusters, antiproton annihilations

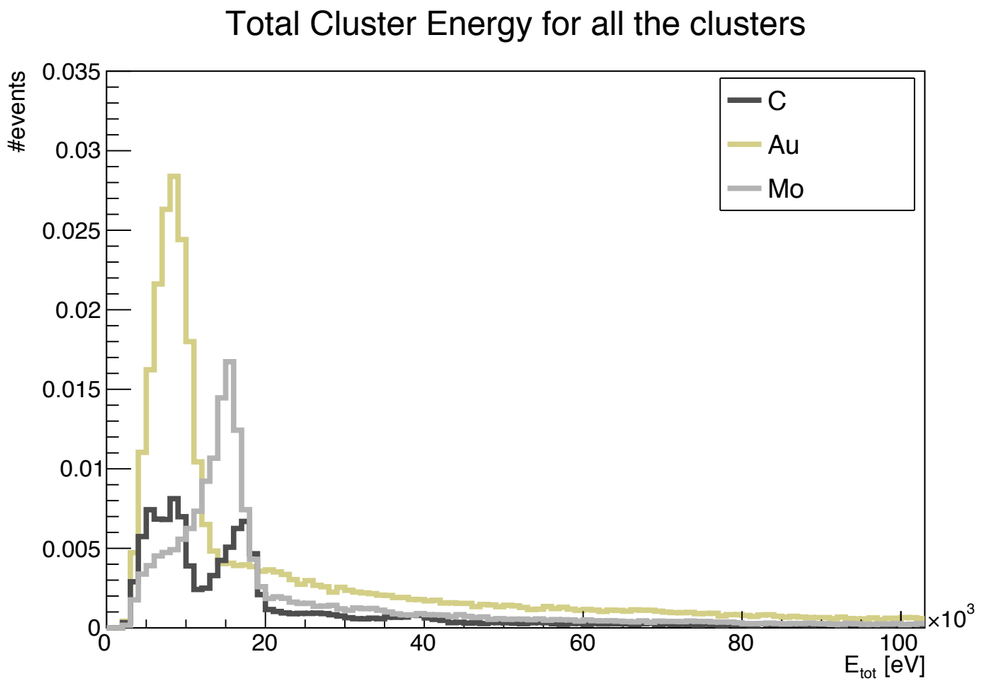


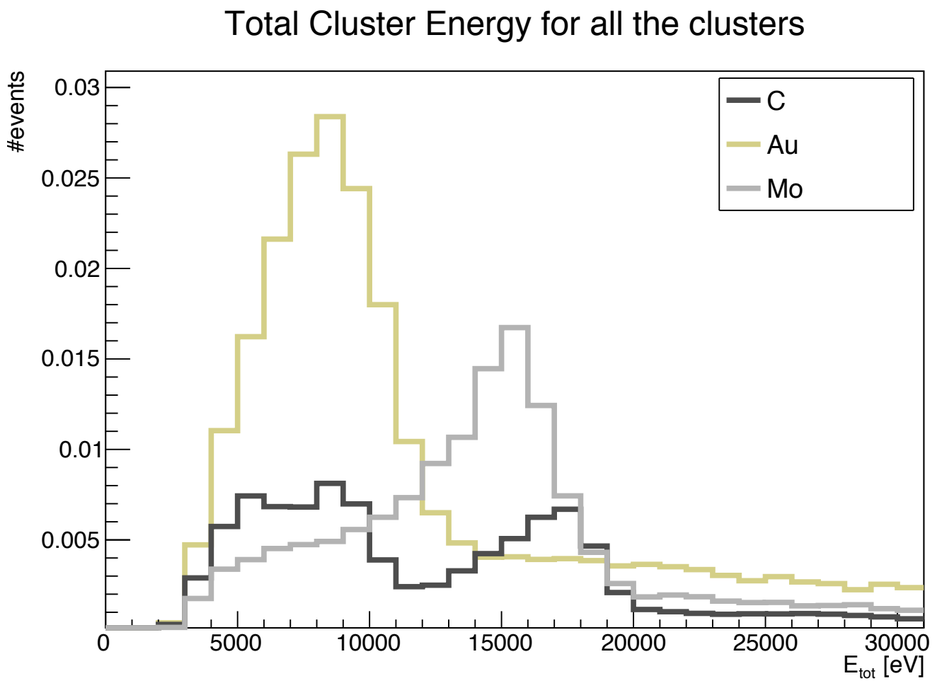
Total energy deposited from all clusters, cosmics



Energy deposited in a cluster, DATA

- **Low energy gamma in the DATA**
  - **C: ~5 keV, 9 keV, 17-18 keV.**
  - **Mo: ~15-16 keV.**
  - **Au: ~9 keV.**

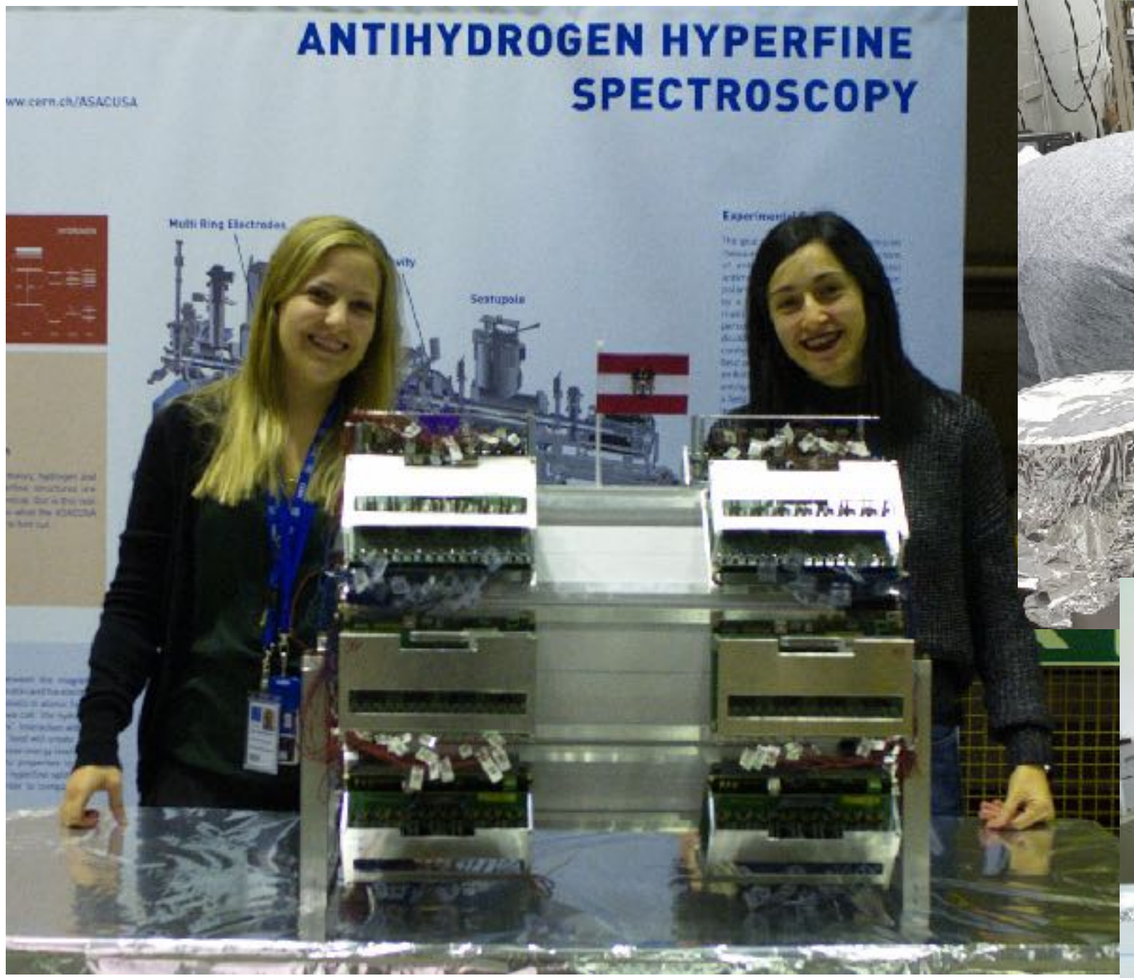




Conclusions and further work

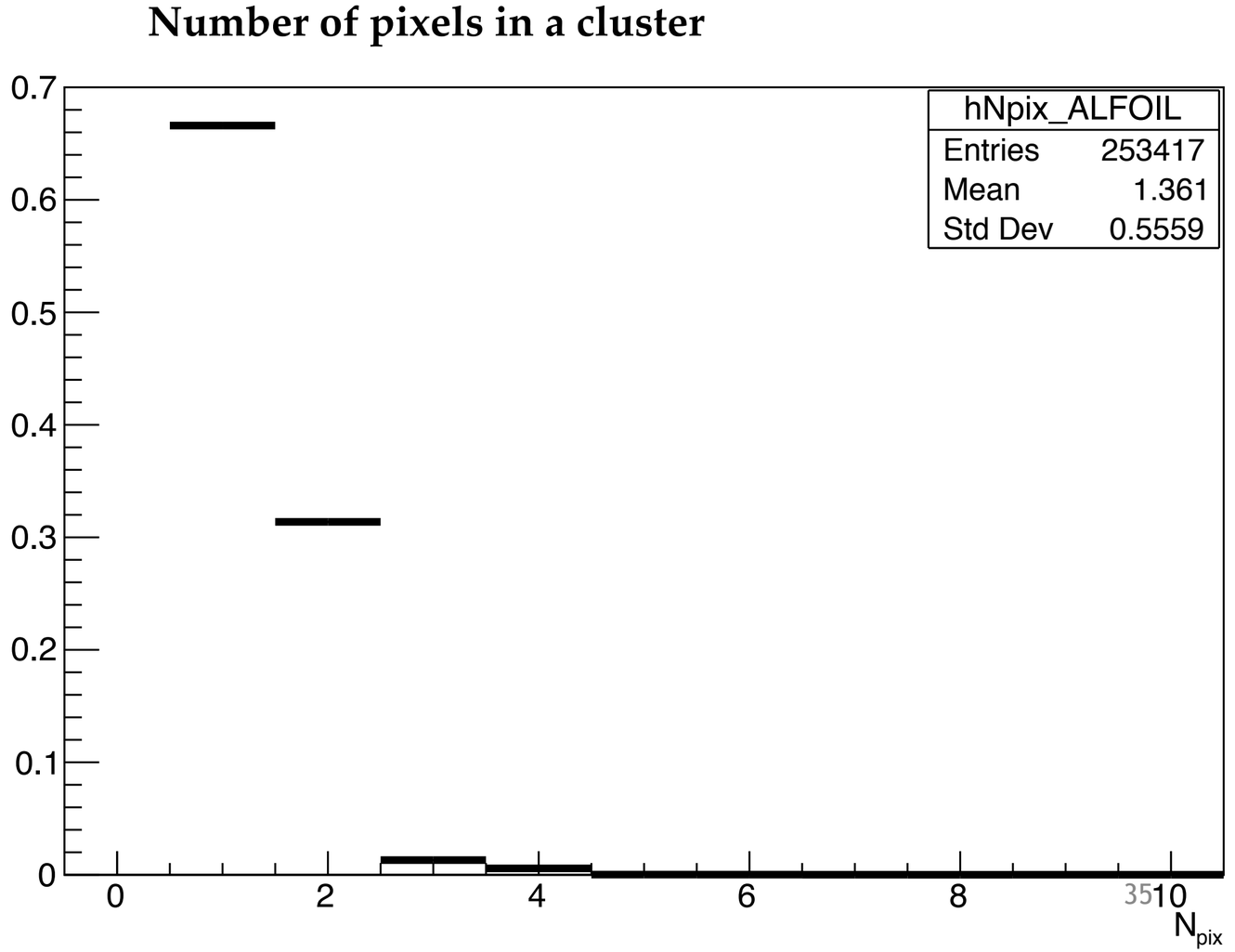
- **Data were taken for antiproton annihilation at rest:**
  - **Carbon, Molybdenum, Gold.**
- **Comparison of the number of prongs/annihilation for CHIPS and FTFP.**
- **Analysis on the deposited energy from the annihilation prongs.**
  - **Energy calibration to be included in the simulations.**
- **More refined particle discrimination.**
- **FLUKA simulations in progress.**
- **3D reconstruction of the annihilation vertex and combined analysis from Hodoscope and Timepix3.**

Thank you!


ANTIHYDROGEN HYPERFINE
SPECTROSCOPY
Multi Ring Electrodes
Sextupole

Data with Am241 source

- **Clusters with 1, 2, 3 and 4 pixels respectively.**
  - **1pix: 66.6%**
  - **2pix: 31.4%**
  - **3pix: 1.31%**
  - **4pix: 0.57%**
  - **5+ pix: 0.15% (the number is compatible with the number of comics expected during the data taking).**



MIP in silicon

- Distinguish between gammas and pions that cross the detector (almost) perpendicularly and produce small clusters.
- 200 eV/um - 600 eV/um for 500 um thick Si detector -> 100 keV - 600 keV energy deposit with MPV ~ 135 keV.
- 3.6 eV per e-h pair, ~80 e-/um for MIP -> ~150 keV on average.
- Data with cosmics: gammas are also present in cosmics, combined analysis are undergoing.
- Data is needed with pion beam and/or > 60 keV gammas.

Energy loss for 500 MeV pion in silicon